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THESIS

IGNITION SYSTEM REQUIREMENTS AND THEIR APPLICATION TO THE DESIGN OF CAPACITOR DISCHARGE IGNITION SYSTEMS

by

Terrence Lyle Williamson

Thesis Advisor: R. W. Adler

December 1971

83

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Ignition System Requirements and Their Application
to the
Design of Capacitor Discharge Ignition Systems

by

Terrence Lyle Williamson
Lieutenant, United States Naval Reserve
B. S., Weber State College, 1965

Submitted in partial fulfillment of the
requirements for the degree of

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Author: Terrence Williamson

Approved by: R W All
Thesis Advisor

Sydney R. Parker
Chairman, Department of Electrical Engineering

Milton U. Clauser
Academic Dean

ABSTRACT

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This study examines wave-front requirements at the spark plug for producing ignition in the internal combustion engine and system characteristics necessary for producing the wave-front. Arc requirements are described and used to define CDI parameters.

A modified Kettering system which violates some basic ignition concepts was replaced by a CDI system designed in this study. Its characteristics were derived from arc requirements, not by aggrandizing the replaced battery-coil parameters.

During performance tests, the CDI system exhibited superior performance. It fired simulated fouled plugs and continued to produce an arc when pressurized to 3 times the value at which the Kettering ceased to function. This improved performance was accomplished with approximately the same stored energy and less input power.

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I. INTRODUCTION

The ignition system currently used on the majority of automotive engines has been improved only slightly since its introduction in 1914 by Charles F. Kettering. This pioneer system, referred to as the battery-coil or Kettering ignition is incapable of keeping pace with the demands put on it by todays engines.

This study deals with the requirements necessary to produce ignition of a fuel-air mixture in an automotive engine combustion chamber. Ignition requirements are divided into arc characteristics for proper ignition and system requirements to produce this arc.

To evaluate the processes used to produce the arc, various ignition systems are discussed. Their basic operation and characteristics are described to give insight into ignition system requirements.

A specific, modified battery-coil ignition system is described and its characteristics listed. This system is described in detail since a capacitor discharge ignition, CDI, system is designed to replace it. Characteristics of both systems were evaluated and the improved operating characteristics of the CDI system noted.

Ignition requirements are established and are applicable to new ignition system principles. These requirements are applied to the design of the system.

This study concludes by recommending the implementation of CDI as the standard ignition for modern automotive engines.

II. IGNITION SYSTEM PARAMETERS

Abundant literature exists on ignition systems and on the spark characteristics necessary to assure ignition of the explosive charge in the combustion chamber. The difficulty arises in ferreting out what requirements are necessary and applicable; the sources of information are not all in agreement on just what parameters should be considered in the design of an ignition system.

This section defines ignition parameters and their relationship to proper ignition.

A. SPARK PLUGS

The spark plug is that portion of the ignition system producing the arc that ignites the fuel-air mixture. If the arc does not have proper characteristics, ignition will not take place and misfiring will result. It is the duty of the ignition system to supply the necessary voltage and energy to the spark plug.

Also, the spark plug is the common element in all ignition systems. Regardless of the driving source configuration, the plug produces ignition by an arc occuring between electrodes. Gap configurations may vary, but arc generation and its characteristics remain basically unchanged.

1. Fouling

Fouling can be attributed to metallic compounds found in combustion deposits. These materials, accumulating on the insulator firing end, become electrically conductive, under certain operating conditions, and can thus prevent the ignition voltage from building up sufficiently to fire the plug.

Fouling is caused by many factors such as: engine make and model, engine power utilization, spark plug design and heat range, anti-knock additives and other fuel additives, and oil consumption. It occurs due to accumulation of deposits under low temperature (low output) or high temperature (high output) conditions.

Dry, fluffy black carbon deposits result from overrich carburetion, excessive choking, or a sticking manifold heat valve. Low ignition output can reduce voltage and cause misfiring. Excessive idling and slow speeds under light load also can keep spark plug temperature so low that normal combustion deposits are not burned off.

Deposits accumulating on the insulator are by products of combustion and come from the fuel and lubricating oil, both of which today generally contain additives. Most powdery deposits have no adverse effect on spark plug operation; however, they may cause intermittent missing under severe operation conditions, especially at high speed and heavy load. Under these conditions the powdery deposits melt and form a shiny yellow glaze coating on the insulator which, when hot, acts as an electrical conductor. This allows the current to follow the deposits instead of jumping the gap.[1]

The average driver cannot operate in a range that will best prevent fouling. He is likely to be subjected to both types of fouling since he will drive under low output while in city traffic yet in a high output situation on the expressways. This requires the ignition system to fire a fouled plug under all engine operating conditions.

2. Fouled Plug Simulation

As discussed above, a fouled plug will present a conductive shunt path for the ignition current. A high voltage noninductive resistor connected from the spark plug to ground may be used to simulate a fouled plug.[2,3] This resistance is usually in the range of 0.5 to 1.0 MΩ. The 1 MΩ. test is intended to simulate system performance with a fouled plug and is an industry standard test.

B. SPARK PARAMETERS

To ignite the fuel-air charge in an internal combustion engine, the spark must meet certain criteria. The basic parameters effecting the spark are gap width, high tension voltage, spark duration, rise time, and energy.

Figure 1 is the waveform observed on an oscilloscope placed across the gap of a spark plug. Areas 1 and 3 represent the ignition voltage rise time and arc sustaining voltage duration respectively. The arc is struck at point 2 and extinguished at point 4.

1. Gap Width[3,4,5,6]

Cycle-to-cycle variations in ignition consistency is related to the condition of the gap. The plug location and purging of the gap are important.

The gap must have a minimum spacing to enable the arc to transfer adequate heat energy to the fuel-air mixture. The mixture has a natural tendency to quench or cool everything within its path. Wetted spark plug electrodes produce boundary layers of fuel-air ratios too rich to ignite.

A wide gap will enhance the circulation of mixtures of ignitable ratios within the gap area. A lean mixture, with greater molecular spacing of

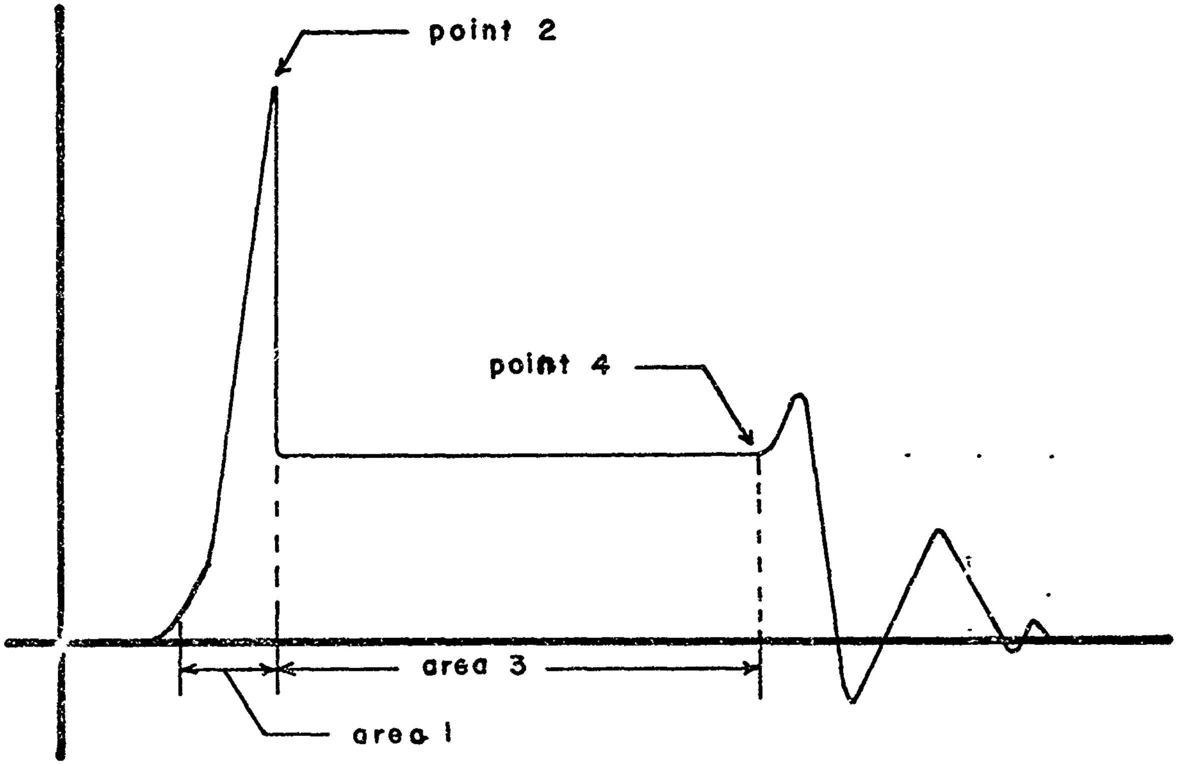


Fig. 1. Spark Waveform.

fuel and air particles, requires a wider gap in order to allow adequate quantities of the mixture within the proximity of the spark for the necessary heat transfer to initiate combustion.

Widening the gap increases the capacitive energy delivered to the gap. This is a result of the increased voltage required to initiate the arc between the electrodes. Since $E = \frac{1}{2}CV^2$, the additional energy available will be proportional to the square of the additional voltage required.

The gap is typically set at the minimum value that provides smooth engine idle. Basically, gap width should be as large as possible but not so large that the ignition harness and distribution system will not handle the voltage required to create ionization. Allowances must also be included for gap growth.

In the past, gap widths have been limited by available ignition voltages. This problem has been diminished and large gap widths, up to 0.050 in., may now be recommended. The limiting factor now is the voltage breakdown of the ignition system components. The gap width should be limited so that the maximum voltage required under the worst conditions is approximately 22 kV.

2. High Tension Voltage Requirements

The voltage required to cause arc-over is dependent on engine design and operating conditions as well as spark plug geometry. Variations from 4 to 20 kV. for various engine operating conditions are not uncommon.[3,6,7,8,9]

a. Compression

The variable which is usually considered first, due to the traditional method of bench testing, is compression pressure. While the absolute value of sparking voltages will vary somewhat depending on the type of fuel,

moisture content and voltage source, this is basically a linear relationship, as indicated in Fig. 2, with the voltage required increasing as pressure surrounding the gap increases. However, because of the nonuniform electric field gradient within the plug gap, the breakdown voltage does not follow Paschen's Law exactly.

In general, Paschen's Law states that the voltage required to jump a given gap in a uniform field is dependent only upon the product of the gas pressure and the electrode spacing. Increased gap size or pressure results in less breakdown voltage than predicted by Paschen's Law.

b. Gap Spacing

Other factors being equal, sparking voltages will increase directly with gap spacing within the normal range of usable settings as shown in Fig. 3. The discussion on Paschen's Law above also applies here.

c. Electrode Temperature

Temperature has a marked effect on voltage requirements. The lower the temperature, the higher the voltage required to cause arc over. This effect is also shown in Fig. 3.

d. Speed and Load

The effects of speed and load in a typical 4-cyle automotive engine are illustrated in Fig. 4. The slight decrease noted at high speeds can be attributed to increased spark plug electrode temperatures and decreased compression pressures which occur as the engine's breathing efficiency decreases.

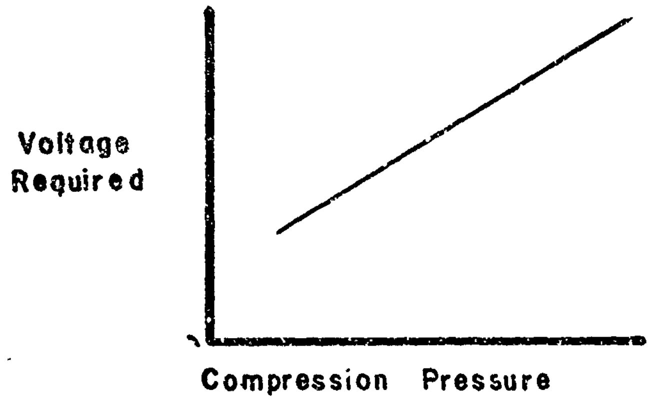


Fig. 2.

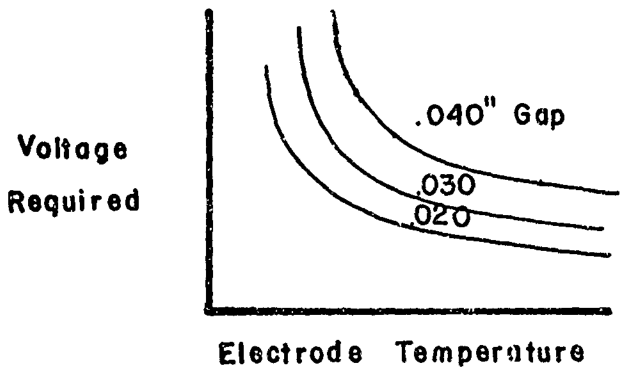


Fig. 3

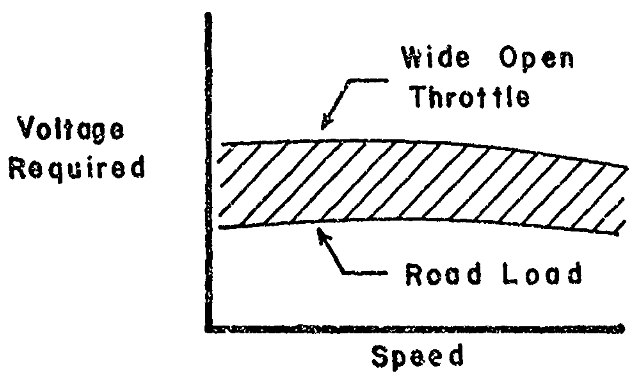


Fig. 4

e. Acceleration

Sudden, wide-open-throttle acceleration causes rapid but temporary rises in voltage requirements as shown in Fig. 5. This increase is attributed to the rapid increase in pressure. The effect here is greater than that due to temperature, since the spark plug electrodes have not had time to heat up.

These sudden voltage increases are transient in nature and explain why misfiring is often encountered first during periods of rapid acceleration.

f. Ignition Timing

The typical effect of spark advance on voltage is illustrated in Fig. 6. Advancing ignition timing lowers voltage requirements because the spark plug fires at a lower pressure, and the electrodes are hotter because of less charge cooling and higher flame temperatures.

If the spark is retarded past top dead center, requirements decrease as compression at the point of ignition drops, and power and temperature are reduced.

g. Fuel-Air Ratio

Lowest voltage requirements will be observed at the stoichiometric ratio as shown in Fig. 7. Leaning of the fuel charge has the greatest effect on voltage requirements, although the overall effects can be considered negligible in the normal range of fuel-air ratios.

h. Voltage Polarity

Voltage polarity, commonly called coil polarity, is an often overlooked yet important factor. It must be considered because on all conventional

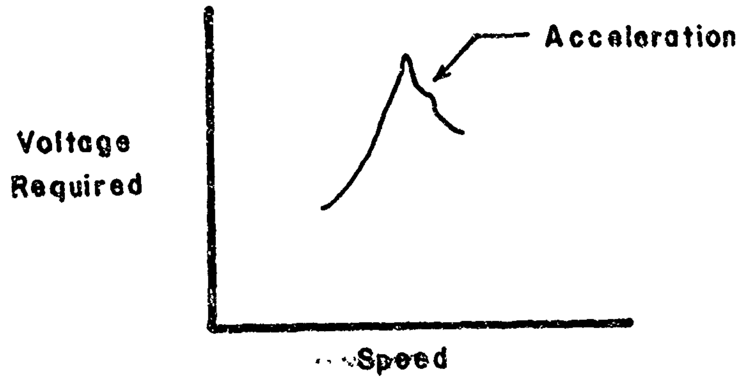


Fig. 5

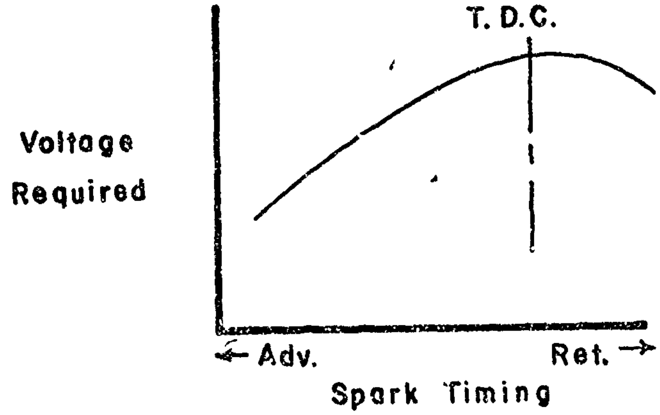


Fig. 6

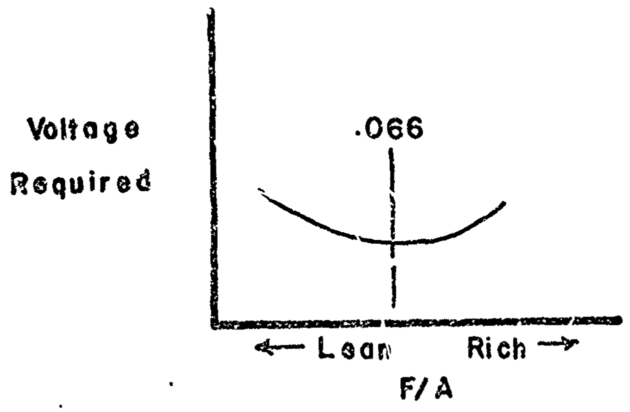


Fig. 7

spark plug designs, the center electrode operates considerably hotter than the ground electrode. Electron theory states that electrons move more readily from the hot to the cold electrode than the inverse. Therefore, the voltage applied to a plug must rise in the negative direction in order to produce ionization at minimum voltage.

If the plug has reverse polarity with respect to that defined above, the firing voltage is greater. In some instances, the difference may be a few thousand volts.

i. Electrode Condition

Sharp or pointed electrodes concentrate the gap ionization by increasing the electric field gradient. Therefore, spark plugs can be expected to require progressively greater voltage as the sharp corners of the electrodes erode away and become rounded in normal service.

Fouling deposits do not influence the arc-over voltage, unless the deposits are within the gap area, which is seldom the case.

j. Overview of Voltage Requirements

The maximum available voltage from the coil should not exceed 30 kV. as any voltage higher than this can produce undue strain on the ignition harness, distributor, and spark plugs. At any voltage exceeding 30 kV. the spark plug insulation can flashover either internally or externally, and similiar flashovers can occur within the distributor either from the cover electrodes to ground or between electrodes. These flashovers can form carbon paths that once started can seriously down-grade engine performance.

Manufactures of electronic ignition systems have advertised voltages as high as 60 kV., pursuing the theory that if some is good, more is better and the more voltage, the better the system. Actually, under worst conditions, an engine should not require more than 22 kV. across the plug to establish ionization. Under normal conditions, the peak voltage is considerably lower than this. The objective of an ideal system would be to produce the required voltage at any engine speed while maintaining the proper energy for the required length of time.

3. Spark Duration

Optimum spark duration for ignition of the fuel-air mixture has not been determined. Values range from a microsecond to thousands of microseconds.

At present, spark duration requirements are evaluated on test engines where the duration that provides the highest engine output is considered optimum. This procedure does not demarcate the requirements for ignition of the combustible mixture, but rather the deficiencies that exist in combustion chamber design.

For ignition to take place there must be a combustible mixture between the spark gap. Longer spark durations have a higher probability of igniting a mixture that is not homogenous throughout the combustion chamber. Long arc durations give sufficient time to permit the fuel charge to come within the gap area.

Ignition timing has a large control over the turbulences that exist in the combustion chamber. Figure 8 illustrates the effect of ignition timing

and spark duration on engine output. Analyzing Fig. 8 more closely, it is seen that spark duration has limited effect on engine output if the specified engine timing is used, therefore, overadvanced timing is avoided.

Practically all of todays automotive engines use the battery-coil ignition system with spark durations typically 1,000 to 2,000 usec. Current references on ignition systems recommend long duration times of 500 usec. or more, where possible. However, an example of the ability of the capacitive portion of the discharge to initiate combustion has previously been demonstrated with the piezoelectric ignition system developed by Clevite Corporation in the early 1960's. The entire pulse width of the system was only 860 nsec. which is less than the rise time of a conventional magneto.

Theoretical discussions on ignition systems indicated that a system with such short duration would not fire the mixture, but the piezoelectric system does fire the mixture and very well too.[10]

Due to combustion chamber variations from engine to engine, and even from cylinder to cylinder in the same engine, it is recommended that the spark duration be at least 100 to 200 usec. in duration. If the combustion chamber and engine design are satisfactory this duration will be sufficient to ignite the fuel-air mixture.

4. Voltage Rise Time

From examining various ignition systems, their past history and theoretical arc considerations, it appears that voltage and energy are not the only criteria of ignition system operation. Many of the systems that are capable of firing fouled spark plugs exhibit shorter rise times than the battery-coil

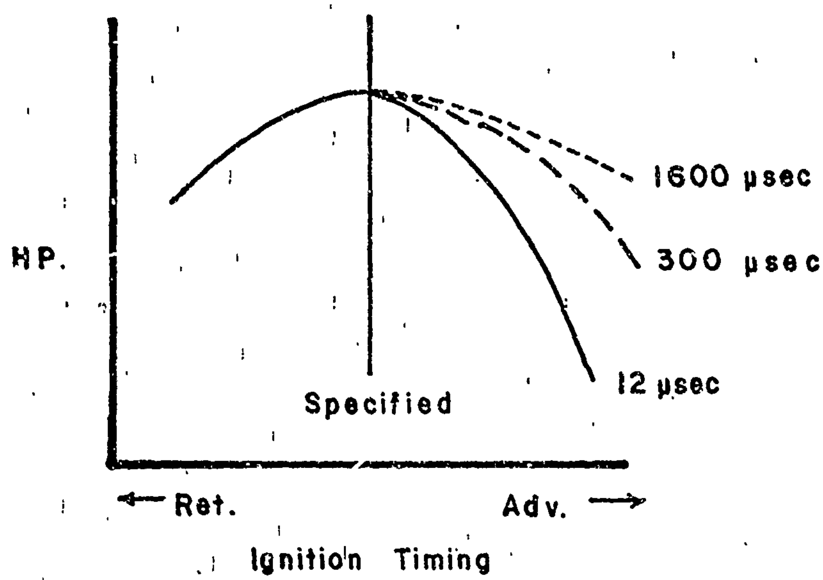

HP.
1600 μsec
300 μsec
12 μsec
Specified
← Ret.
Adv. →
Ignition Timing

Fig. 8

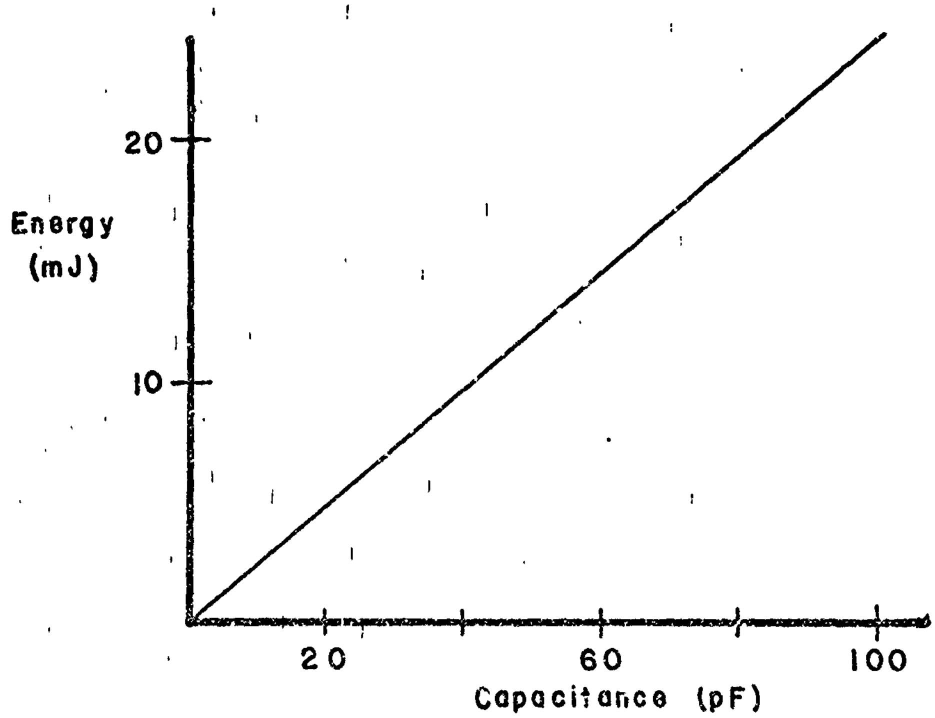

Energy
(mJ)
20
10
20
60
100
Capacitance (pF)

Fig. 9

system. It is concluded that rise time must be included in ignition system evaluation and design. For example, in referring to the piezoelectric system mentioned earlier, the rise time for this system was not measured exactly but was less than 10 nsec. Some investigations indicate it may be as short as one nsec. This short rise time system ran an engine six times longer between plug replacement than a longer rise time magneto; yet, in some circles, the magneto is thought to be the ultimate.

Rise time is defined as the duration required for the voltage to build up and fire a spark plug. If this time is short, there is less opportunity for the energy to be dissipated in carbon deposits, moisture, and other partial conducting paths. Also, a short rise time is more effective in ion formation.

Paschen's Law must again be evaluated in the realm in which it was written, namely that the electric field is uniform and that the voltage is slowly applied. For a short rise time pulse, the gap voltage may be reduced below the value considered normal by at least 15 percent.

Shorter rise times have the disadvantages of larger radiation losses (increased radio interference), increased requirements on the system to prevent crossfiring, and more chance of developing unwanted carbon paths.

An optimum ignition pulse would have sufficient rate of voltage rise to permit firing of heavily fouled plugs without the need for large total pulse energy. The rate of rise should be consistent with the voltage breakdown of the ignition system components. A rise time between 10 and 30 usec. should prove adequate for most cases.

5. Energy Requirements

Total energy is important, in that a certain minimum energy is required for ignition, but the required energy depends to an extent on the rise time and pulse width of the arc. Energy levels higher than necessary to account for the variables are detrimental to spark plug life. Since the energy level required for the standard mixture may be as low as 0.002 mJ., typical ignition system energies are higher than necessary.[10] In general it is considered that 1 mJ. is sufficient to produce ignition of the fuel-air mixture.

The energies mentioned above are those required to raise a small amount of mixture to combustion temperature. Further, this quantity of energy is actually a very small part of the total energy a system must have. Literature on system requirements list system energies from 10 to 40 mJ. These large energy requirements, compared to that required for combustion, are due to system losses and capacitances. If losses are neglected, energy requirements reduce to $E = \frac{1}{2}CV^2$. Assuming that under all operating conditions 22 kV. is sufficient to arc across the gap, Fig. 9 shows the energy required to overcome system capacitance. If a short rise time system is used little energy will be dissipated prior to the arc. Once the arc is struck, the capacitive energy is released rapidly in the leading section of the arc; inductive energy is released slowly increasing arc duration.

Energy requirements should be held to a minimum. If excess energy is delivered to the arc, no improvement in combustion is noted, furthermore, gap erosion increases. Designers of ignition systems must consider the fact that

only a small, insignificant part of the total energy is required to produce combustion. The majority of system energy is used to assure that the required voltage will be developed.

III. IGNITION SYSTEMS

The contents of this section describe the operation and characteristics of some of the ignition systems in use today in the automobile. Two ignition systems that are not in wide spread use are also discussed. This section covers both the non-electronic and electronic systems.

A. KETTERING IGNITION SYSTEM

Since 1914, automakers have used the Kettering or inductive ignition system--a battery, ignition coil, and cam-driven mechanical switch. Most of the automobiles sold in the U. S. come equipped with this system. Fig. 10 is a representative schematic diagram of a typical Kettering system.

Referring to Fig. 10, when the ignition switch SW1 and the cam operated contacts SW2 close, current will flow through primary P of ignition coil T, building up magnetic flux. The current will reach a maximum value limited by the resistance of the primary. As the cam rotates, contacts SW2 are separated by the cam lobes, interrupting primary current. The distributor contact capacitor C1 suppresses contact arcing and forms an oscillatory circuit with the equivalent primary inductance of T.

Interruption of the primary current causes the flux in the ignition coil to collapse. The collapsing flux self-induces a voltage in the primary and by mutual coupling induces a voltage in the secondary of T. The secondary voltage is related directly to the primary voltage as the ratio of the number of turns in the secondary to the number of turns in the primary.

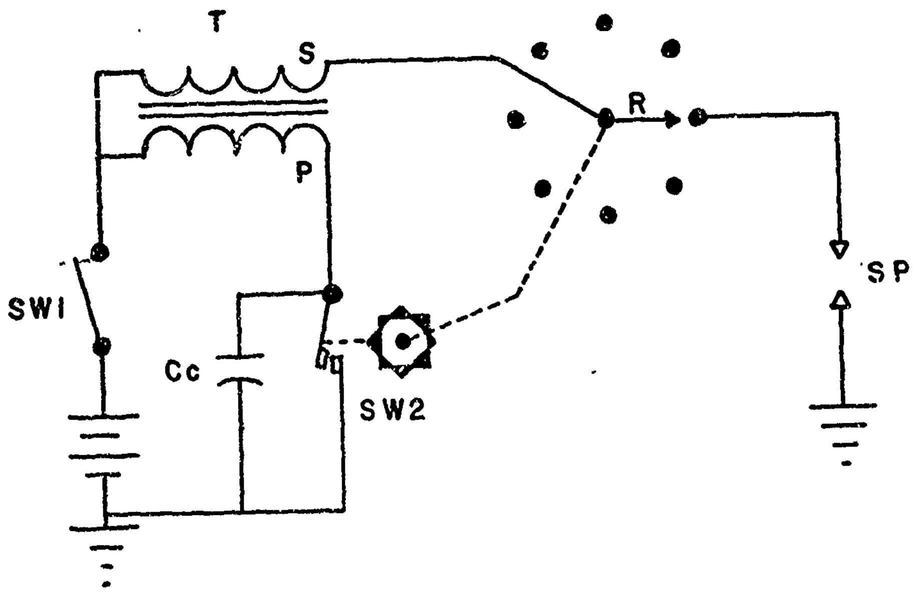

T
S
P
R
SW1
Cc
SW2
SP

Fig. 10

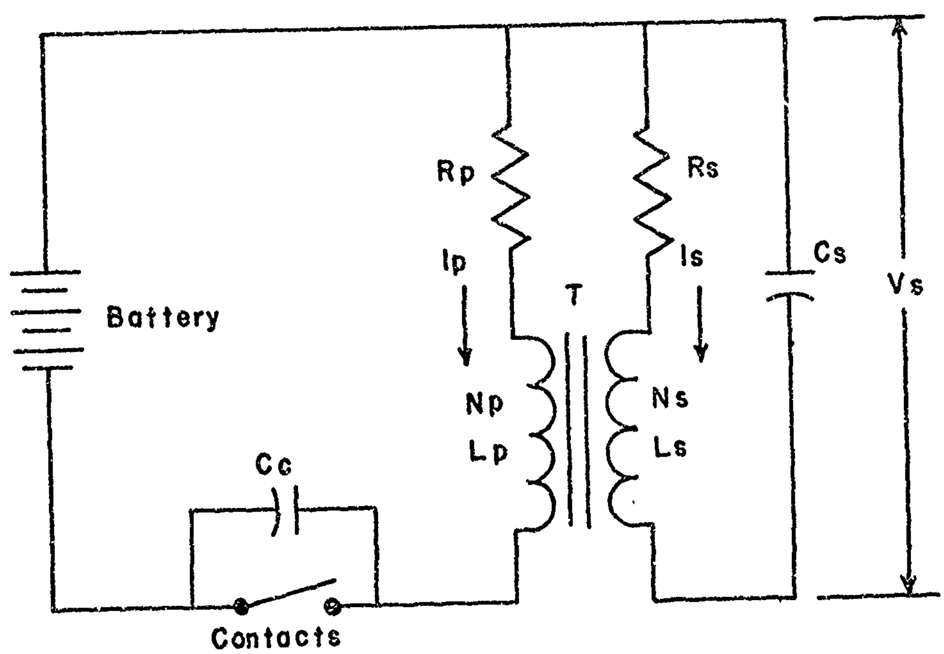

Rp
Rs
Ip
Is
Cs
Vs
T
Battery
Np
Lp
Ns
Ls
Cc
Contacts

Fig. 11

The high voltage causes a spark to jump the small gap between the rotor R and the distributor cap insert with which the rotor is aligned, thereby firing the desired spark plug, SP, connected to the insert by a high tension cable.

Figure 11 is also a schematic of the Kettering system, but contains some of the distributed components that are often overlooked. Cs is the capacitance of the secondary of T and the high tension leads. Rp and Rs represent the internal primary and secondary resistances, respectively, of the induction coil and Cc is the contact capacitor.

If a perfect ignition coil is assumed which is free from loss due to resistance, radiation, and dielectric hysteresis, the coil output energy will be equal to the coil input energy. The input energy in an ignition coil is related to the primary inductance and primary current by the equation:

$$W = \frac{1}{2} L_p I_p^2$$

where: W = energy stored in primary
Lp = primary inductance
Ip = primary current.

The current in an inductive circuit is a function of the time the circuit is energized. If the ignition coil energy is not to decrease by more than 10 percent at some high speed value, the time constant, $T = L/R$, of the coil primary circuit must be one-third of the high speed primary circuit actuation time (contacts closed for three time constants).

It is necessary to evaluate the total energy required in the primary of a coil. Assuming an ideal coil, to elevate the secondary to spark plug firing

voltage,

$$Wt = \frac{1}{2} \left[Cs + (Np/Ns)^2 Cs\right] Vs^2 \qquad (1)$$

where: Wt = total energy in system
Cs = total secondary capacitance
Vs = secondary voltage
Ns = turns on coil secondary
Cc = contact condenser capacitance.[11]

From the above analysis a typical standard ignition system requires a primary current of 16 amperes. This current must flow through the contacts, however, it is impractical for a contact set to handle this much current on a continuous basis. Therefore, current limitation forces conventional systems to operate at a maximum of about 5 amperes with a resulting decrease in high speed performance.

The disadvantages of the Kettering system are:[12]

1. The large value of current being interrupted by the contact-breaker points, cause excessive erosion.

2. The moving arm of the contact-breaker tends to bounce at high speeds, thus shortening the time the points are closed. Point bounce reduces coil output and also increases point wear.

3. A substantial reduction occurs in the output voltage with increasing engine speed.

4. The system is highly inefficient at low engine speeds due to the high current.

5. The system has a long voltage rise time resulting in poor performance when spark plugs become fouled.

B. HITACHI IGNITION SYSTEM[13]

Examining Fig. 12, it is seen that this system is a modification of the Kettering ignition system described previously. The spark voltage is developed in an identical manner and energy requirements remain the same. The system also has the same disadvantages.

By using the Hitachi ignition system, a 4-cylinder, 4-stroke engine can have the proper ignition sequence without the need for a distributor, and requires only the ignition coil and breaker-plate. The high tension cables are connected directly to the spark plug from the induction coil. By using the dual system as shown, dwell time is doubled over that for a Kettering system on a 4-cylinder engine. This improves high speed performance since primary current will have a longer time to build-up to the design value.

The system has some major drawbacks that require discussion, dealing with the way in which the voltage is delivered to the plugs. Notice that two plugs are fired simultaneously in series with respect to the induction coil termination. This is permissable, since one plug fires on the power stroke while its mate fires on the exhaust stroke.

The disadvantage is that higher potential must be developed to produce arcs in two plugs in series instead of just one. Since one plug is firing on the exhaust stroke, the potential required will be much less than that for the plug firing on the compression stroke. The main disadvantage, however, is that one plug is being fired with reverse polarity. As mentioned earlier, a plug fired with reverse polarity requires a few thousand volts more.

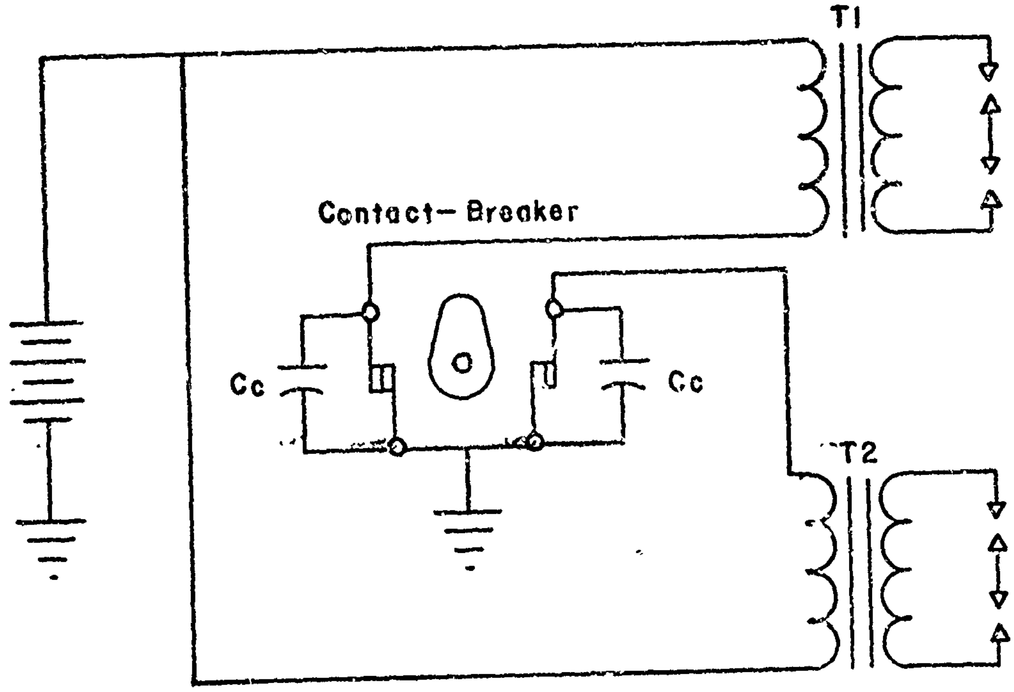


Fig. 12. Hitachi Ignition System

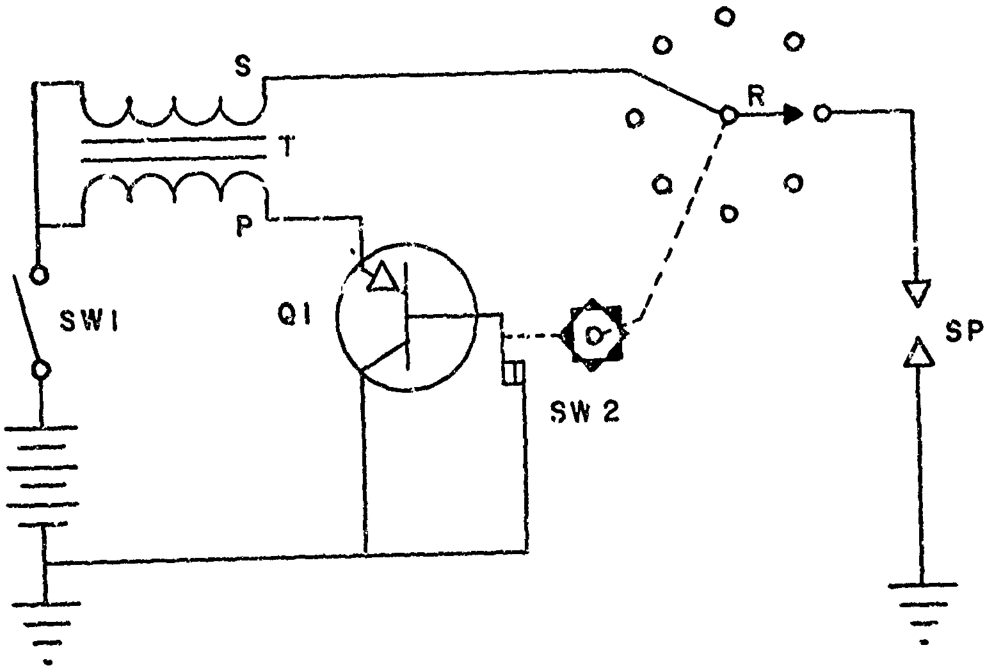


Fig. 13. Transistor Ignition

This system must still adhere to requirements that ignition voltage be between 25 kV. and 30 kV. To compensate for the need for higher ignition voltage, the spark plug gap is reduced slightly to lower the arc-over potential. This reduction in gap width will of course decrease the arc area available for the fuel-air mixture to circulate.

The reason for considering this particular ignition system is that an electronic ignition system was designed in this study to replace it.

C. PIEZOELECTRIC IGNITION

The piezoelectric ignition system has not been commercially used on production engines. Its introduction here is to inculcate the point that rise time, being of little concern to ignition system designers until recently, should play a larger part in the design of systems and to point out that extremely long arc durations in the thousands of microseconds are not required to produce combustion of a homogenous fuel-air mixture.

This ignition system derives its name from the piezoelectric generation of electricity in a crystal structure when pressure is applied. System operation is exceptionally simple in theory. The potential difference generated by a crystal, a stack of crystals in series, when struck sharply by mechanical means is applied to the spark plug. The voltage rise is extremely rapid and the energy delivered to the arc is strictly capacitive, therefore, the arc is of short duration. As mentioned before, the characteristics for this system are in the nanosecond range.

Older theoretical discussions indicate that an ignition system with this short rise time and pulse width can not fire the mixture. This system has

run an engine six times longer between plug replacement than has a magneto with its long rise time and arc duration. It can start an engine after the spark plug has been soaked in water and put into the engine dripping wet.[10]

D. TRANSISTORIZED IGNITION SYSTEM

The use of a transistor switch was one of the first attempts to use semiconductors to improve the Kettering ignition system. The transistorized system is essentially identical to the conventional one except for the addition of transistor Q1, Fig. 13. The discussion of the Kettering system, section III. A., is applicable.

The difference is that the primary current is now switched on and off by a transistor instead of the contact-breaker. The contact condenser is also eliminated with only the small collector to emitter capacitance in the primary circuit. The points control the base current thus turning Q1 on and off. The small current in the base does not cause the points to erode as rapidly as in the Kettering system. A light or magnetic sensing device can be connected to the base of Q1 to turn it on and off, thus eliminating the points entirely.

By eliminating the points, a larger primary current can be used to improve high engine speed performance, the higher currents being obtained by reducing the primary inductance. This usually results in an increased turns ratio. Standard Kettering ignition systems usually have a turns ration of 100:1 while the transistorized systems have a much higher turns ratio, often in the vicinity of 250:1 to 500:1.[14]

Although the transistor ignition system produces a more constant voltage throughout the engine speed range, it still has a long rise time and puts a large demand on the battery and charging curcuit due to the requirement for increased primary current. Under starting conditions, this system may not perform satisfactorily. During cold weather operation it is often inferior to the battery-coil ignition system.

The transistorized system was used on some production automobiles. It was soon discontinued since the small improvement in ignition high speed performance did not warrant its additional cost. Cold weather starting reliability was also less than the standard system.

E. CAPACITOR DISCHARGE IGNITION SYSTEM (CDI)

Capacitor discharge ignition systems have been on the market for a number of years. The CDI system was used as an electronic ignition long before transistorized ignitions were introduced. Figure 14 is a block diagram of a typical CDI system. In the early systems, the dc-to-dc converter was of the mechanical vibrator design and the gate was a thyratron tube. It was unreliable, yet produced superior ignition.

The CDI system remained obscure until the advent of semiconductor components. With the introduction of power transistors and the SCR, the dc-to-dc converter was easily produced using blocking transformers and the thyratron was replaced by its counterpart, the SCR. This ignition is challenging the Kettering system as the one for todays high performance engines, in fact, one

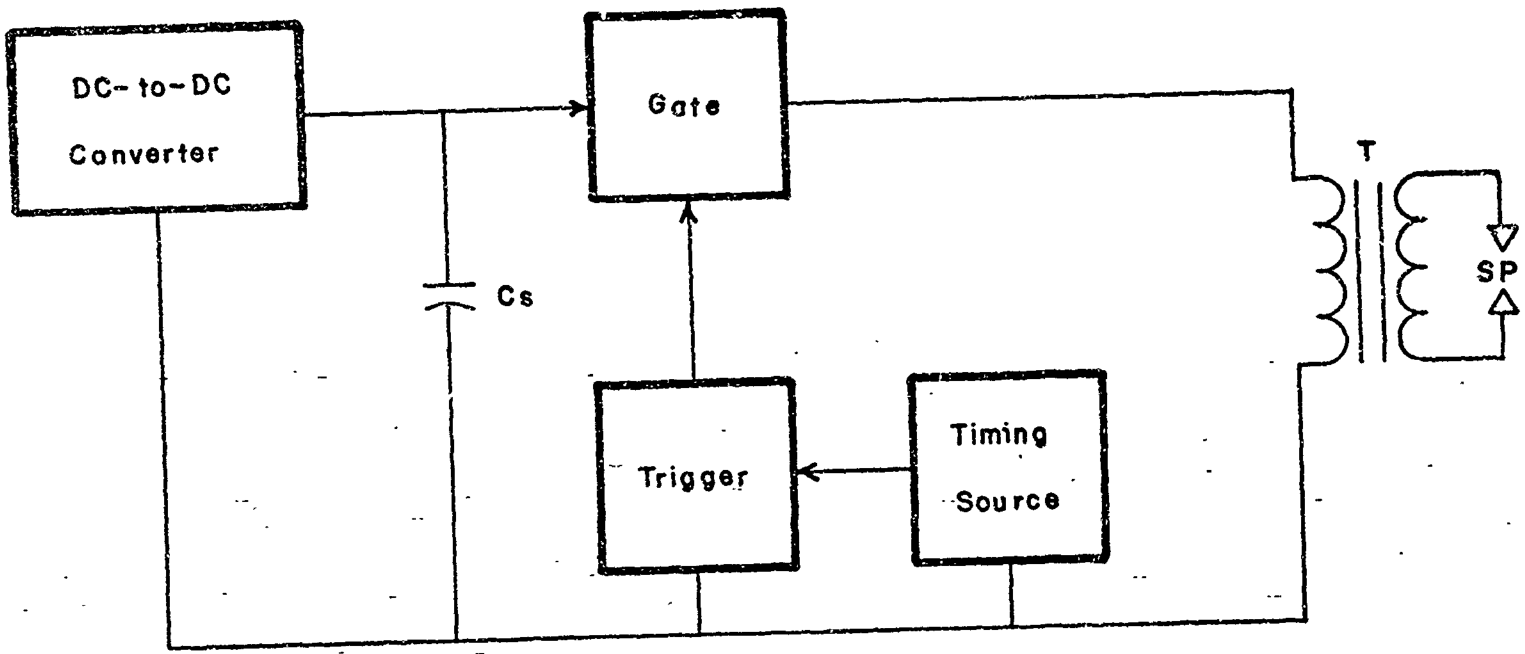


Fig. 14. CDI Block Diagram.

auto manufacture is using a CDI system as standard equipment on one of its 1972 models. It had been offered as an option at a substantial price prior to this time.

1. Operation

There are two ways in which to use the ignition coil to produce the high voltage pulse. First is the rate-of-change of current, or inductive mode. This is the mode in which the Kettering system operates. Second is the transformer mode. In this mode the coil acts only to transform a low voltage to the high voltage required. It is this second mode in which the capacitor discharge system functions.

The dc-to-dc converter increased the low battery voltage to an intermediate level of a few hundred volts. The output charges the capacitor, referred to as a storage capacitor, to the intermediate voltage. At the proper time for ignition, the trigger circuit opens the gate which in turn connects the storage capacitor across the ignition coil. The capacitor voltage is then multiplied by the transformer's turns ratio to produce the high voltage for ignition. By using the transformer mode a much shorter rise time can be developed. The ignition coil can be designed to have low inductance and thus act as a pulse transformer. This can result in an ignition system with an extremely short rise time.

Ignition coil primary pulse duration is shorter than the response time of the secondary. This means that even a capacitor storage type system does store some energy in the transformer magnetic field momentarily.[15] If it was not for this magnetic field storage, the capacitor energy would be delivered

very rapidly to the arc resulting in a very short duration pulse. It is the energy stored in the inductance that extends the arc duration since, as mentioned earlier, inductive energy is released slowly.

Storage capacitor Cs must supply energy for the same reasons as discussed previously in regard to inductive systems.

Conduction of the gate connects Cs through the reflected impedance of the transformer to the secondary capacitance of the ignition system. Equating the energies on both sides of the perfect transformer and solving for Cs yields:

$$Cs = \frac{Vs^2\, Cd}{Vp^2 - Vs^2\, (Np/Ns)^2} \qquad (2)$$

where: Cs = energy storage capacitance
Vs = secondary voltage
Vp = Cs voltage before SCR conducts
Cd = secondary distributed capacitance
Np = primary turns, ignition coil
Ns = secondary turns, ignition coil.

The above relationship holds for all values of voltage and capacitance when losses due to imperfect transformer action are neglected.

2. CDI, Improved Ignition Characteristics

The CDI system stores the energy required for ignition in a capacitor. This form of storage has the advantage that once sufficient energy has been accumulated in the capacitor, no more energy is consumed by the system until the capacitor has to be recharged for the next firing. This means that the system will draw only the energy it needs and therefore, current requirements

will vary as engine speed. In terms of energy requirement verses speed, the CDI system has a higher efficiency and improved utilization of energy drawn from the battery.

The CDI system, with its shorter rise time, provides better performance in firing fouled plugs. P. C. Kline of Delco-Remy reports that their experience with the Delco CD system shows plug life 4 to 5 times longer than with conventional ignition.[9] FIAT, on their sports cars, used the CDI in extending the thermal range of the spark plug so that a cold spark plug can be used for highway operation, and at the same time avoid misfirings due to cold fouling at low speeds.[9]

One definite benefit is improved starting, particularly in damp weather, or in very cold weather. CD equipped engines tolerate carburetor flooding and other problems that cause starting difficulties.

Champion Spark Plug Company studied the effect of capacitor discharge ignition on electrode erosion.[16] Champion noted that spark plug gap growth was much less when using the capacitor discharge ignition system with the fast rise time and short arc duration. In fact, the spark plug gaps from the capacitor discharge system actually decreased slightly due to a light deposit build-up. Gap growth measurements are not a true indication of overall deterioration. Center electrodes from the conventional system were round while the electrodes from the capacitor discharge system still had relatively sharp edges. Sharp edges are desirable since they reduce the voltage required for arc production.

The trigger circuit for a CDI system can be designed using a light or magnetic sensor instead of the customary contact-breaker.

An ignition system having the above characteristics, if its electronics were properly designed, would require a great deal less maintenance than the standard battery-coil ignition. Since the contact-breaker assembly could be eliminated, the only wear would be in the shaft bearings of the distributor assembly. Once ignition timing was initially set, it would not need resetting unless major maintenance was necessary on the distributor. The need to remove spark plugs for cleaning, regapping, or replacement is greatly reduced, thus, greatly extending plug life.

The CDI system has the characteristics that are badly needed on todays automotive engines. This system, if properly designed, could be the long-needed replacement for the 1914 Kettering ignition system.

IV. IGNITION SYSTEM DESIGN REQUIREMENTS

The contents of this section define the requirements one must consider in the design of ignition systems. Presented are current ideas on ignition system design. Applying these concepts will result in systems which appear to be better solutions. However, some procedures, if followed, might give only a brief reprieve from the problem the system was to eliminate before introducing problems of its own.

A. BRUTE FORCE CRITERIA

If some is good, more must be better! R. G. Van Houten and J. C. Schweitzer of Delta Products states, "Any new ignition system must meet the following requirements:"

1. "Output energy levels should exceed present levels by substantial margins. A new system should be able to develop energies of 40 milliwatt-seconds minimum, and be easily controlled to set this level higher if necessary. The energy output and voltage levels should remain constant, over an rpm range of 8,000 to 10,000 on eight-cylinder engines."

2. "As rapid a voltage rise time as possible."

3. "It should be low cost and designed for high volume production."[17]

In the description of another system, the following statement is made, "It has been pretty well established that a minimum of 30 milliwatt-seconds of energy is required at the spark plug in modern ignition systems. C1 has been chosen to give 80 milliwatt-seconds, allowing ample reserve energy."[18]

Again the system designer thinks in terms of brute force, "... we find that it takes about 40 kV. to operate the spark plugs. This 40 kV. should be considered a minimum requirement. To assure complete combustion, this value should be exceeded if possible." [14] (Manufacturers of electronic ignition systems have advertised voltages as high as 60 kV.)

Referring to previous discussions on ignition system requirements, energy requirements are related more to system losses than to the energy required to ignite the fuel-air mixture. Energy requirements necessitate careful system evaluation and not the setting of a blanket value. The energy is not held in reserve as mentioned above, but any excess energy, over that required to ignite the mixture and compensate for system losses, is dissipated in the arc and leads to excessive electrode erosion. Some German aircraft during World War II used a high energy CD system to facilitate cold starts. Because of the high energies involved, spark plug life was only 25 hours.

Under normal operation, a spark plug requires only about 4 to 8 kV. to produce an arc. However, since the engine will be operating under various load requirements, a voltage of 22 kV. is considered ample.

B. GENERAL DESIGN REQUIREMENTS

Following is a number of design criteria to be considered in the design of ignition systems.

1. Use as short a voltage rise time as practical, not necessarily as short as possible. With a sufficiently short rise time, an ignition system can more readily fire fouled plugs. In selecting the upper limit on rise time, capacitance loading, corona loss, and insulation failure become of paramount importance.

2. A new ignition system must be more reliable than the system it replaces. Reliability includes the time and cost of maintenance.

3. If the system is not original equipment, installation should require a minimal change in components or wiring.

4. Input power should vary as engine speed.

5. Use energy levels only sufficient for operation.

6. Gains should be made by well known ignition practices related to voltage, namely:

a. Keep the capacitance of the ignition leads as low as possible by keeping them away from metal parts.

b. Reduce secondary series resistance to that required for radio suppression.

c. Use short leads.

d. Reduce corona losses, and hysteresis of coils and capacitors.

e. Develop only sufficient voltage to assure that an arc can be produced at all engine load and operating conditions. A small voltage reserve may be applied, but should not be overdone.

7. If the system is designed to replace an existing one, leave the original system intact so that it may be readily reconnected in case the new system fails.

8. Be able to operate at temperatures in the engine compartment, preferably as high as 250^{o} F., to permit installation directly on the fire wall.

C. SPECIFIC REQUIREMENTS FOR A SYSTEM WHICH IS TO REPLACE THE HITACHI IGNITION SYSTEM

Figure 27 is a table of the characteristics of the Hitachi system. The design parameters for the CDI replacement system conform to, or are improvements on, the Hitachi parameters.

1. Maximum Voltage Requirements

The ignition system was designed to supply 25 kV. optimum but less than 30 kV. to protect high tension components.

2. Spark Plug Gap

The CDI, due to shorter arc duration, uses a wider gap than the conventional system. The Hitachi system gap is set at 0.6 to 0.7 mm.--for the CDI system the gap was widened to 1.0 mm.

3. Spark Duration

Arc duration was selected as 200 usec. to assure consistent ignition. The storage capacitor was varied until a value was established that optimized between spark duration and energy required.

4. Storage Capacitor and Energy Requirements

By equating energy on both sides of the ignition coil, equation (2) was derived. This was used in calculating the energy storage capacitor, which in turn was used to establish how much energy was stored. The parameters used were:

Cs = 0.2 uF. from equation (2)
Cd = 20 pF.
Vp = 600 V.
Np = 380 turns
Ns = 15,000 turns.

The stored energy calculated, 36 mJ., is close to the 30 mJ. standard discussed earlier.

5. Rise Time

Rise time of the voltage pulse applied to the high tension circuit will not be shorter than 10 usec. so that corona and radiation loss will be held to a minimum. Rise time is to be no longer than 30 usec. to reduce energy loss and high speed timing error.

There is no direct way to control rise time in the design of this system since the original ignition coil is used. By the use of a capacitive discharge through the coil, response of the coil was improved resulting in a shorter rise time.

The use of the original ignition coil, rather than a specially designed transformer, was one of the factors evaluated.

6. Power Input Requirements

In section IV.B.4., a storage energy of 36 mJ. per ignition pulse was calculated. Maximum input power is required at maximum engine speed. The ignition system must fire a 4-cylinder, 4-stroke engine, delivering peak bhp. at 8500 rpm. A design margin of 1500 rpm. is included yielding a maximum design rpm. of 10,000.

At maximum rpm. the ignition system requires, for storage capacitor energy, 12 watts assuming 100 percent efficiency. Taking into consideration

the efficiency of the dc-to-dc converter, the power to operate the trigger circuit, and sufficient current to keep the contact-breaker clean, an efficiency of 70 percent is assumed. Thus, system power input is less than 17 watts at an engine speed of 10,000 rpm.

7. Summary of Design Criteria

Listed below is a summary of the requirements considered as goals in the design of the Hitachi replacement:

1. Maximum engine speed is 10,000 rpm.
2. Maximum high tension voltage between 25 to 30 kV.
3. Arc ionization duration is 200 usec.
4. Rise time, 10 to 30 usec.
5. Capacitor storage energy, 30 to 40 mJ.
6. 15 to 20 watts of power consumption from a 12 V. dc. system,
7. Use the original ignition coil,
8. Operate over a temperature range of 0 to 80° C.
9. Design for limited area installation.

V. FEASIBILITY STUDY

Before an attempt was made to design a CDI system, it was realized that a pre-evaluation should be considered to test the feasibility of designing the circuit around the parameters listed earlier. To accomplish this task, the IBM 360/67 digital computer was used in association with the IBM circuit analysis program LISA. During the computer evaluation, circuit parameters were varied to determine their effect on system performance.

To have a means of comparison, the Hitachi ignition system was evaluated, followed by the CDI evaluation.

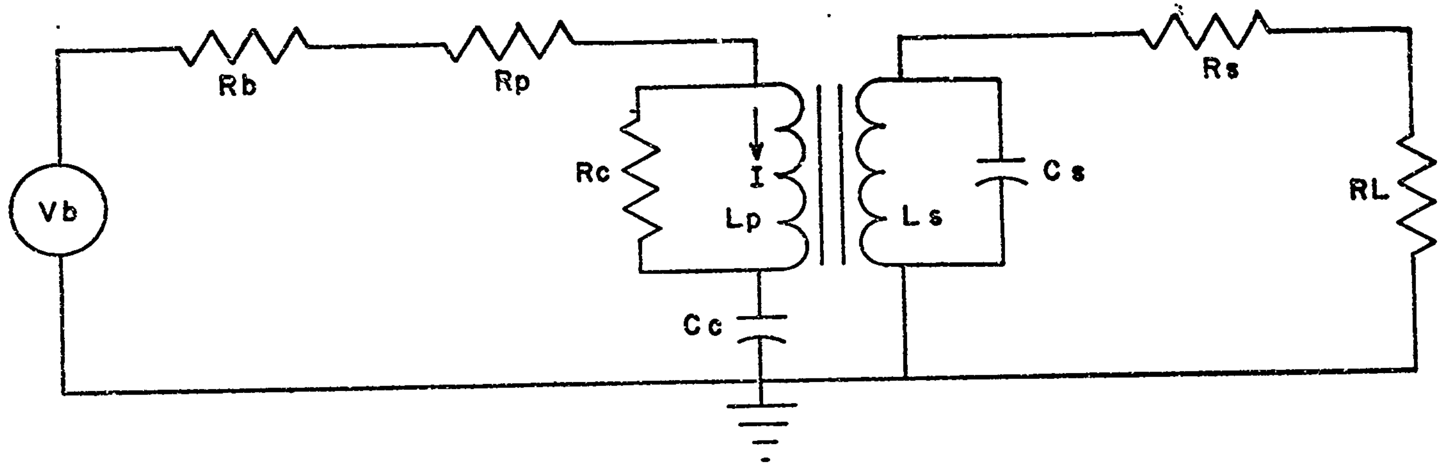
A. HITACHI IGNITION EVALUATION

The Hitachi system was modeled as shown in Fig. 15. Initial condition primary current was calculated from the time the ignition points are closed. The computer solution commenced at the time of point opening.

LISA uses linear nodal analysis techniques. Since the characteristics of an arc are highly nonlinear, a complete solution was unobtainable. The spark plug was replaced with a load resistor, then the computer gave an indication of the system rise time and available ignition voltage. Fig. 16 is a table containing data from the solution.

B. CDI SIMULATION

Of interest was the question, could a capacitor discharging through the primary of the Hitachi ignition coil produce the desired results listed earlier?



Vb = 12V step at time 0
I = Initial Primary Current
Rb = Battery Resistance
Rc = Core Loss
RL = Load
Rp = Primary Resistance
Rs = Secondary Resistance
Cc = Contact - Breaker Capacitance
Cs = Total Secondary Capacitance

Lp = Primary Inductance
Ls = Secondary Inductance
M = Mutual Inductance

Fig. 15. Hitachi Model

	SECONDARY		PRIMARY	
RPM	AVAILABLE VOLTAGE (kV)	RISE TIME (usec)	STORED ENERGY (mJ)	PEAK VOLTAGE (volts)
1,000	20.5	36	57.0	395
5,000	17.1	33	39.6	330
10,000	12.9	34	21.7	244
CDI	31.4	17	36.0	600

Fig. 16. LISA Solution for Hitachi System

To answer the question, the CDI system was modeled as shown in Fig. 17. Rg and impulse driver Vg were used only to implement LISA. Again, due to the nonlinear properties of the arc, the spark plug was replaced with a resistance.

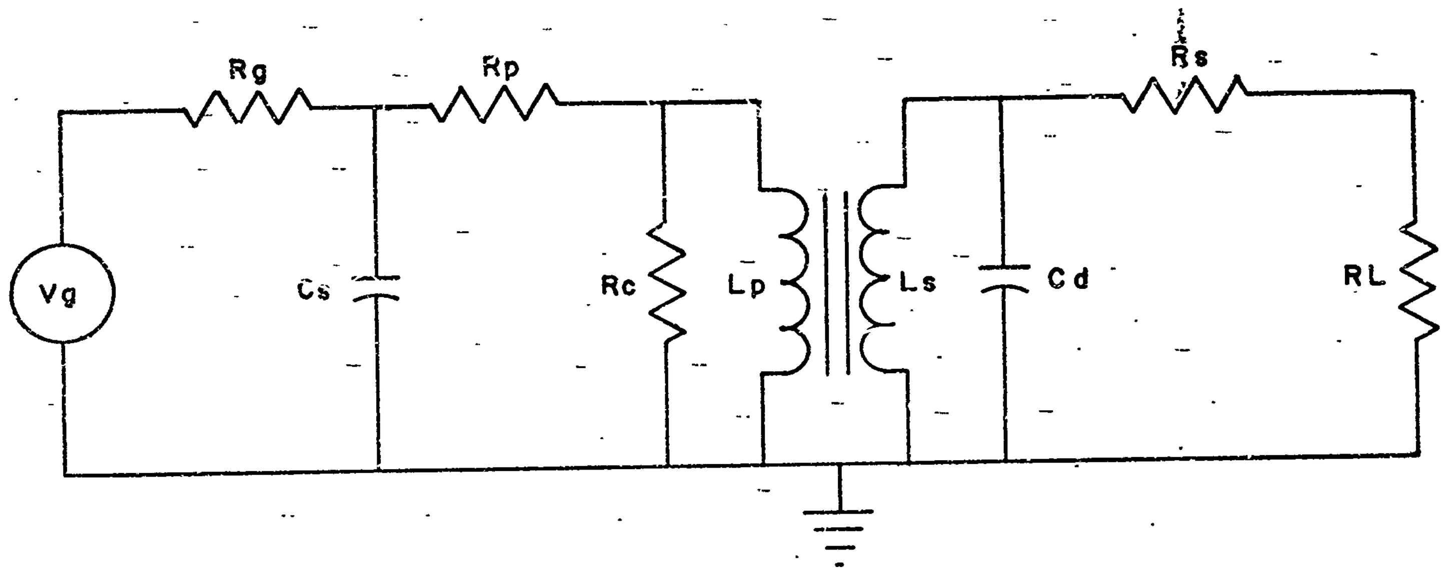
In the analysis it was assumed that the initial condition voltage of the storage capacitor was not affected by engine rpm; this is valid as long as the charging source has a sufficiently low impedance. Therefore, solutions were not obtained for varying engine speeds. However, the storage capacitor value was changed along with other circuit components to evaluate their effects on ignition output.

The computer output verified the selection of a 0.2 uF. storage capacitor. A portion of the solution is shown in Fig. 18. Referring to Fig. 18, the rise time falls between the limit set but the output available voltage is slightly higher than the 30 kV. upper limit.

C. CONCLUSION

The computer analysis demonstrated the superior operation of the CDI system over the battery-coil system even when the same coil was used for both applications. The solution indicates that a system could be designed to meet stated specifications.

On the basis of the computer output, it was decided to proceed and to design a CDI system to replace the Hitachi.



Rc= Core Loss
RL= Load
Rp= Primary Resistance
Rs= Secondary Resistance
Cd= Distributed Capacitance

Cs= Storage Capacitor
Lp= Primary Inductance
Ls= Secondary Inductance
M = Mutual Inductance

Fig. 17. CDI Model

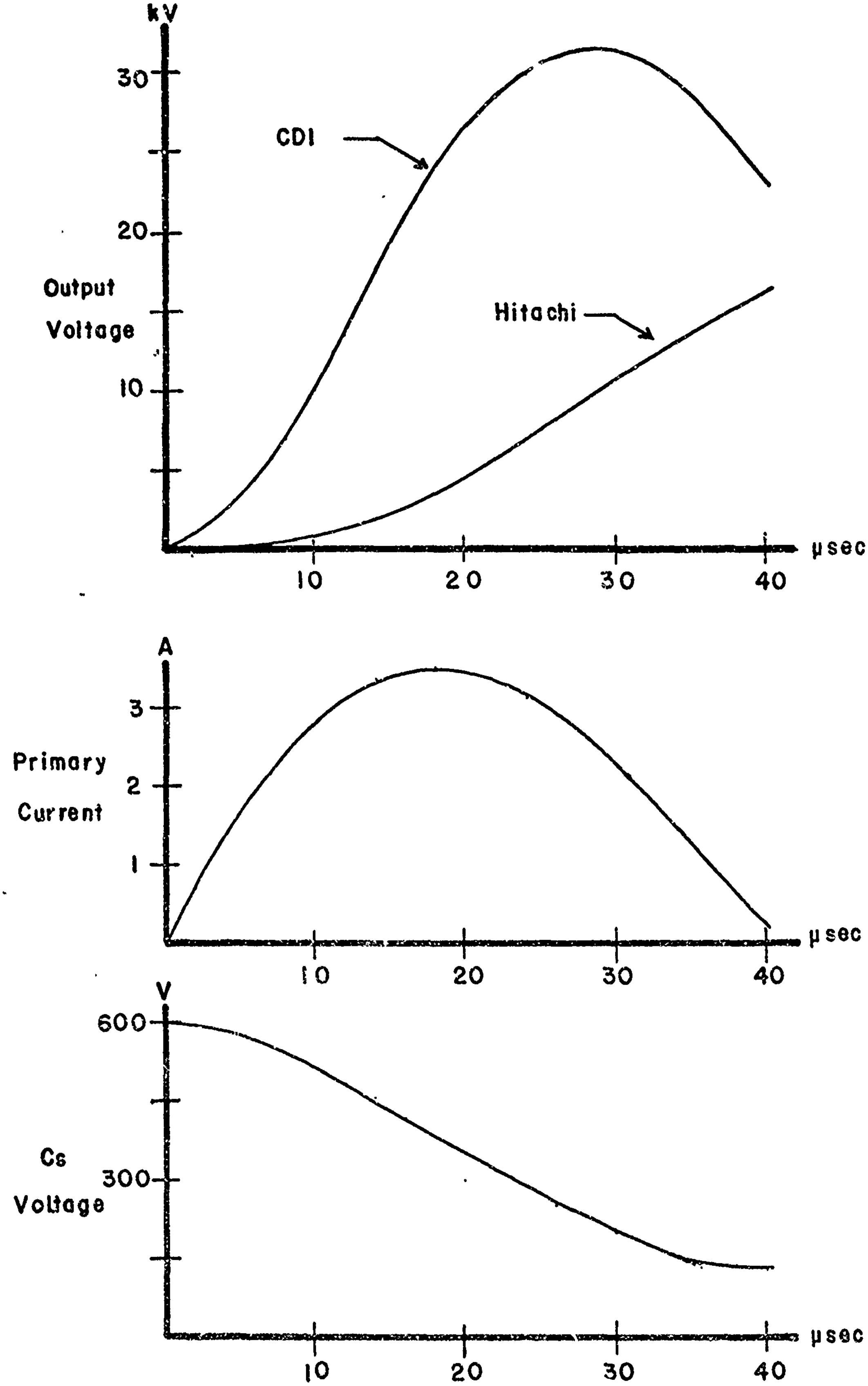


Fig. 18. CDI, Computer Output.

VI. CAPACITOR DISCHARGE IGNITION SYSTEM DESIGN

System design was based on the requirements presented in section IV.B.7. which were adhered to except when situations developed that required modifications.

Reviewing Fig. 12, one sees the Hitachi ignition system consists basically of two Kettering systems each producing an ignition pulse 180 degrees of engine rotation apart. The system can be considered as two independent systems connected together, for ignition timing, by a common breaker cam. Therefore, two independent, identical, CDI systems could be designed to replace the battery-coil system.

To produce a more compact, efficient, and lower cost system, it was decided to design a system having one converter and energy storage capacitor. Here, the circuit branched into two parts, each having its own ignition coil, gate, and trigger circuits. The system block diagram is shown in Fig. 19.

A. DC-to-DC CONVERTER

The function of the dc-to-dc converter is to raise the low battery voltage to an intermediate value to charge the energy storage capacitor.

Basically, the converter circuit will require more space and determine the over-all efficiency of the circuit. To reduce its size and increase its efficiency, the non-saturating circuit was selected over the saturating type. Generally, however, the non-saturating circuit is more complex since it requires an ac power source to excite the transformer, Fig. 20.

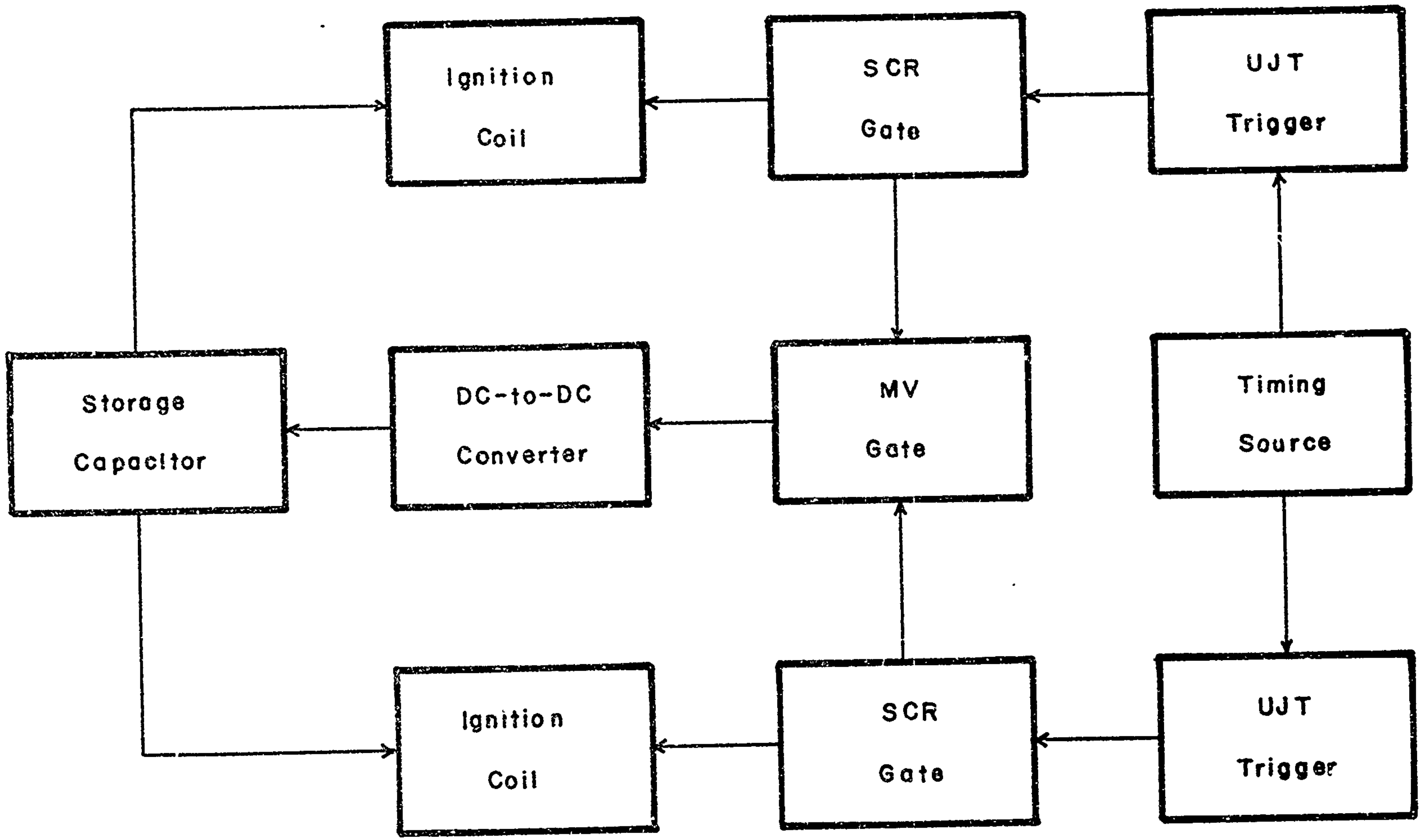


Fig. 19. CDI Block Diagram.

To further reduce the size, a relatively high frequency of 10 kHz. was selected, which permitted the use of a small powdered iron core transformer.

Originally, an intermediate voltage of 600 volts was selected. However, an off-the-shelf inverter transformer was available that transformed the 12 V. battery voltage to 560 V. Referring back to the computer solution, the output voltage exceeded the 30 kV. limit, thus, the lower intermediate voltage will lower the output voltage.

Total time between firings is 3 msec. at maximum engine speed. To assure that arc ionization has ceased and transformer ringing decreased to where the gate can revert to an off state, half of the 3 msec. was allotted for the above. This leaves 1.5 msec. charging time. Since maximum bhp. is developed at 8500 rpm., the storage capacitor voltage was allowed to degrade to 450 V. at 10,000 rpm.

Referring to Fig. 20, transistors Q1 and Q2 act as constant current sources until C3 has charged to about the design value. This is due to the capacitive load on the converter transformer reflecting into the primary as a very low impedance. Assuming a constant current charge, C3, will charge to 500 V. in 1.5 msec. if the secondary of T1 supplies 66.7 mA; this requires a primary current of 3 A.

The astable multivibrator drives Q1 and Q2 at 10 kHz. Q1 and Q2 drives T1 with 3 A. during the charging of C3. When C3 has charged to design value, the output transistors saturate and primary current drops to the minimum value sufficient to keep C3 charged.

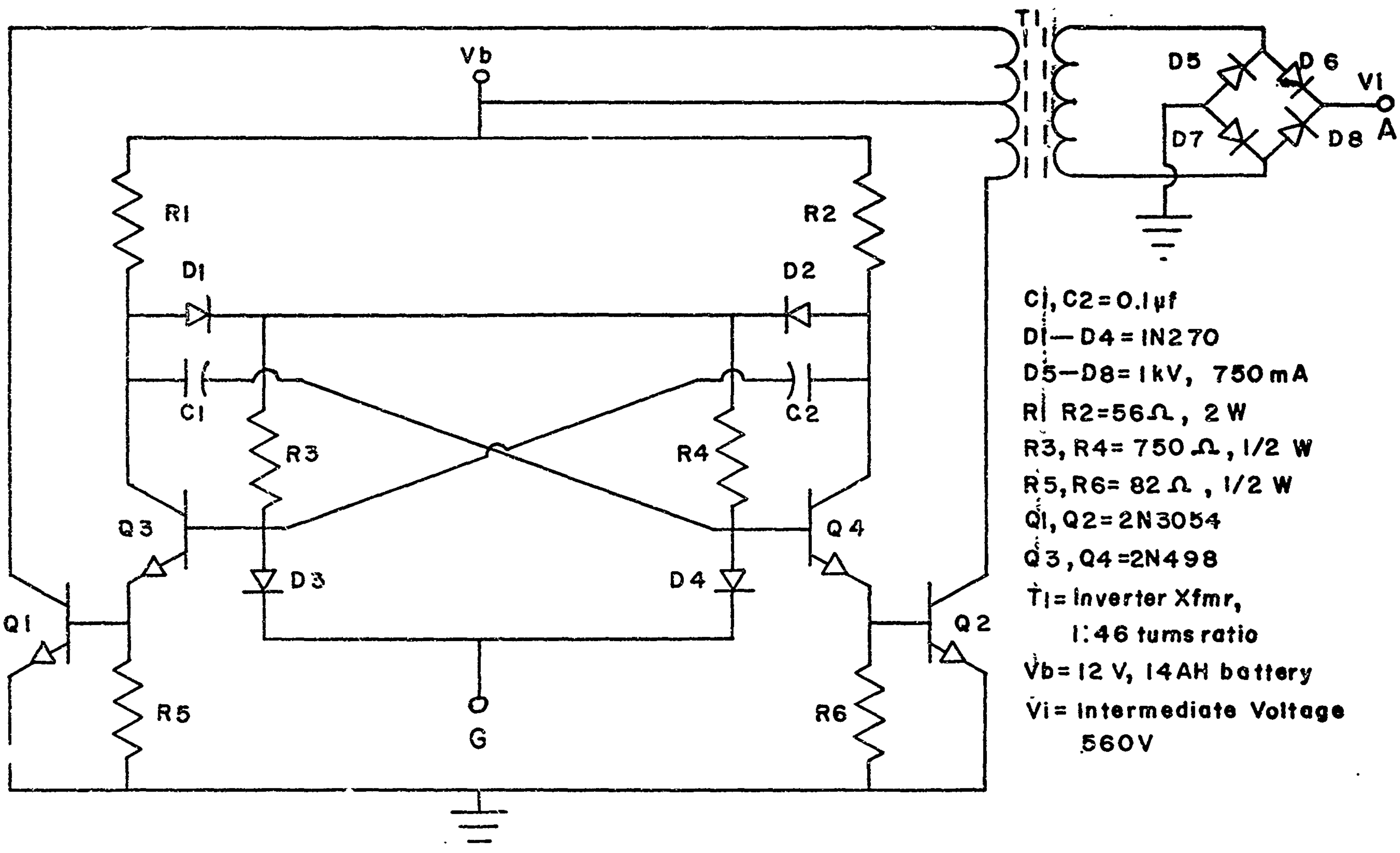


Fig. 20. DC-to-DC Converter

As mentioned earlier, the dc-to-dc converter is gated on and off. This is accomplished by diodes D3 and D4. When terminal G is high, approximately Vb, the diodes are in the off state, and the MV functions normally. If terminal G is low, approximately ground potential, D3 and D4 conduct and clamp Q3 and Q4 bases at ground potential biasing Q1 and Q2 off.

Due to the low resistances in the MV circuit it has a tendency to block. The addition of diodes D1 and D2 prevent blocking.

B. DISCHARGE CIRCUIT AND MV GATE

The schematic diagram of the discharge circuit and MV gate is shown in Fig. 21. When a positive pulse is applied to the gate of the SCR it conducts causing C3 to discharge through the primary of the ignition coil. Before the SCR will revert to the off state, current must be less than the holding current. Q5 is used to apply a turn off pulse to the converter during the time the SCR is conducting. If the converter is not shut down during the discharge portion of the cycle, it will supply sufficient current to hold the SCR on continuously until complete system shut-down.

The MV gate is able to completely turn off the converter over the range of minimum holding current, 0.5 mA., to peak primary current of 3.52 amperes. The gate is basically an RTL circuit with a NOR positive logic function. Either input, when either SCR conducts, clamps the gate output to ground potential, thus, biasing the MV off.

Since the SCR current varies over a large range, the current sensing device should be nonlinear producing a sufficient signal at low current to

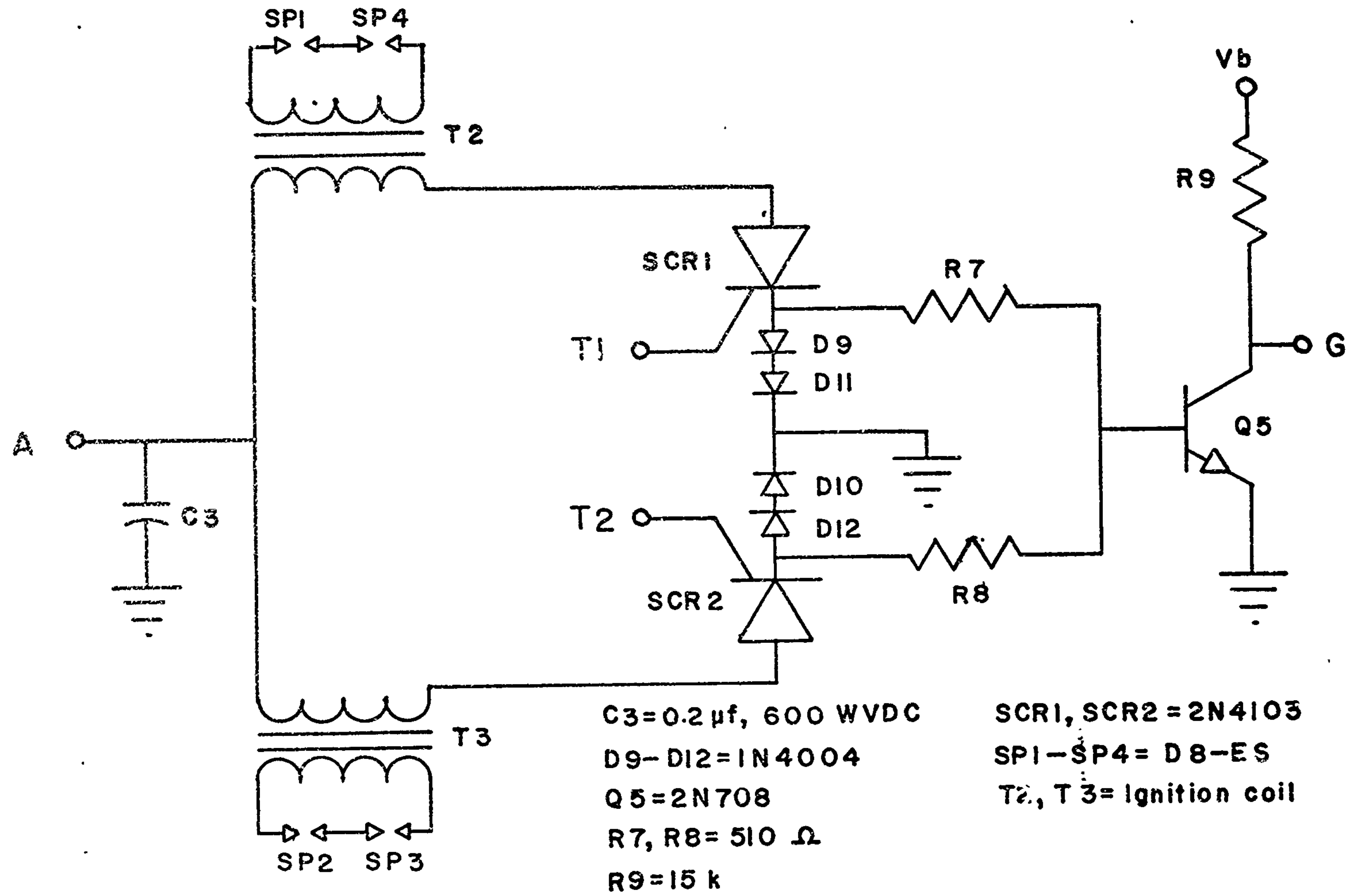


Fig. 21. Discharge Circuit and MV Gate.

keep Q5 saturated, yet at high current the sensor output will not damage the base-emitter junction of Q5. This requires a device having high resistance at the holding current but low resistance at the peak primary current.

To accomplish this, diodes D9 through D12 were connected as shown. At low currents, the diodes will not conduct unless cut-in voltage is exceeded. The cut-in voltage for the two diodes in series is sufficient to hold Q5 at saturation. The voltage drop across the diodes when peak current is applied remains sufficiently close to the cut-in voltage to prevent excessive base current in Q5.

C. SCR TRIGGER CIRCUIT

The original breaker-plate for the Hitachi system remains as the ignition timing source. This simplifies mechanical alterations and permits the ignition to be readily switched back to the original battery-coil system if the CDI system fails.

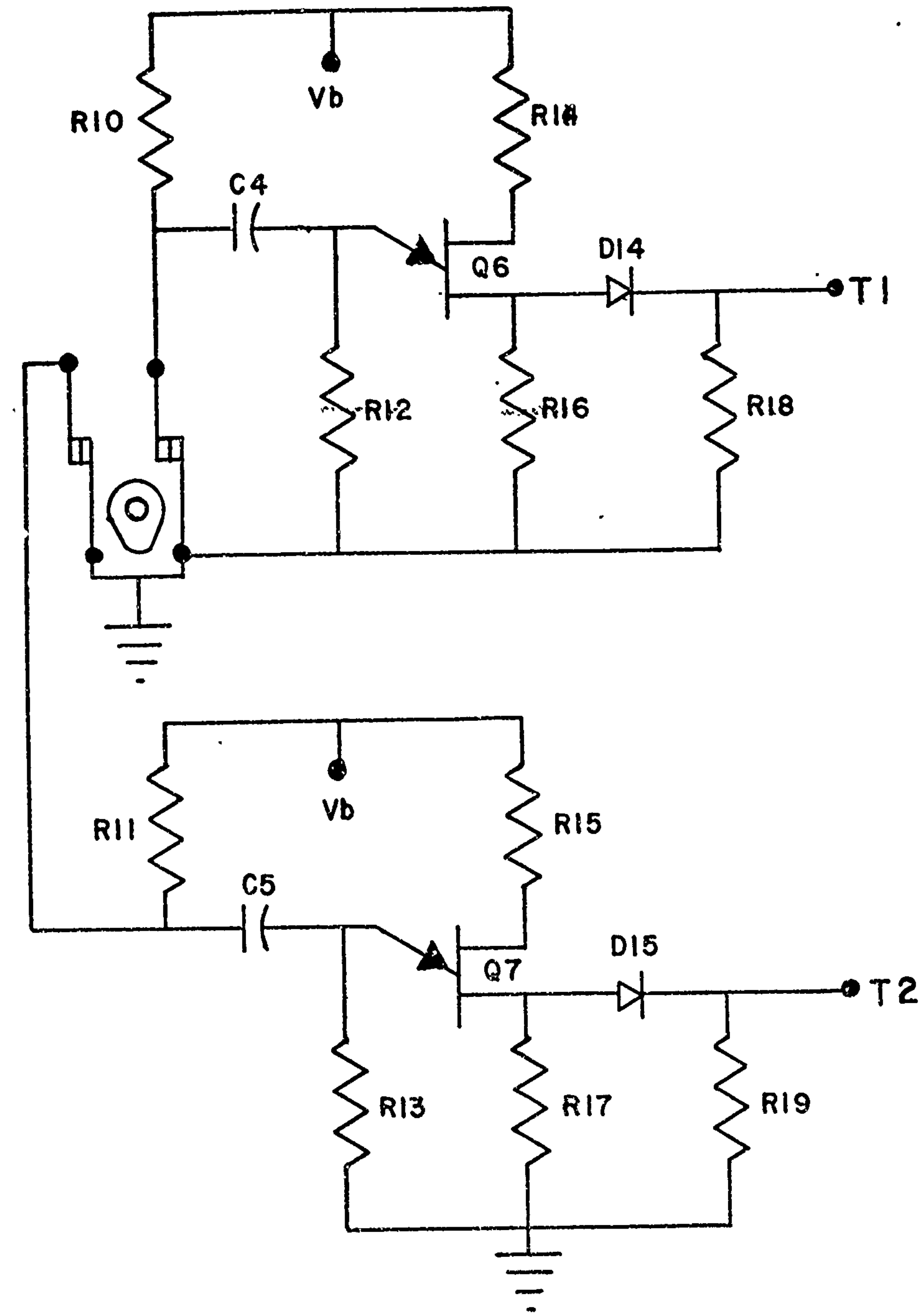
The unijunction transistor, UJT, trigger circuit is shown in Fig. 22. The circuit produces a 5 V. peak pulse of 50 usec. duration. Referring to Fig. 23, it is seen that the output of the trigger circuit is capable of triggering the SCR over a wide temperature range. The SCR operates within its dissipation limits and, Fig. 24, has a turn on time of 1 to 3 usec.[19]

UJT Q6 will not conduct as long as the ignition contacts are closed. When the contacts open, Q6 conducts and charges C4 through R12, Q6, D14, and the low resistance of the SCR gate. After approximately 5 time constants, the pulse applied to the SCR has returned to zero. Therefore, the values of the above components determine the RC time constant, thus, the pulse duration. When

the points close, C4 and R14 are chosen so that the UJT can not be retriggered until 1 msec. has elapsed, thus preventing false triggering during the time the points have a tendency to bounce.

Resistor R12 is selected to provide sufficient current flow to keep the points clean, but, not to cause excessive erosion.

A complete schematic diagram of the CDI system is shown in Fig. 25.



C4, C5 = 0.1 μf
D14, D15 = IN270
Q6, Q7 = 2N1671
R10, R11 = 110 Ω , 2 W
R12, R13 = 11 K
R14, R15 = 500 Ω
R16, R17 = 220 Ω
R18, R19 = 1.1 K

Fig. 22. UJT Trigger.

FORWARD GATE CHARACTERISTICS

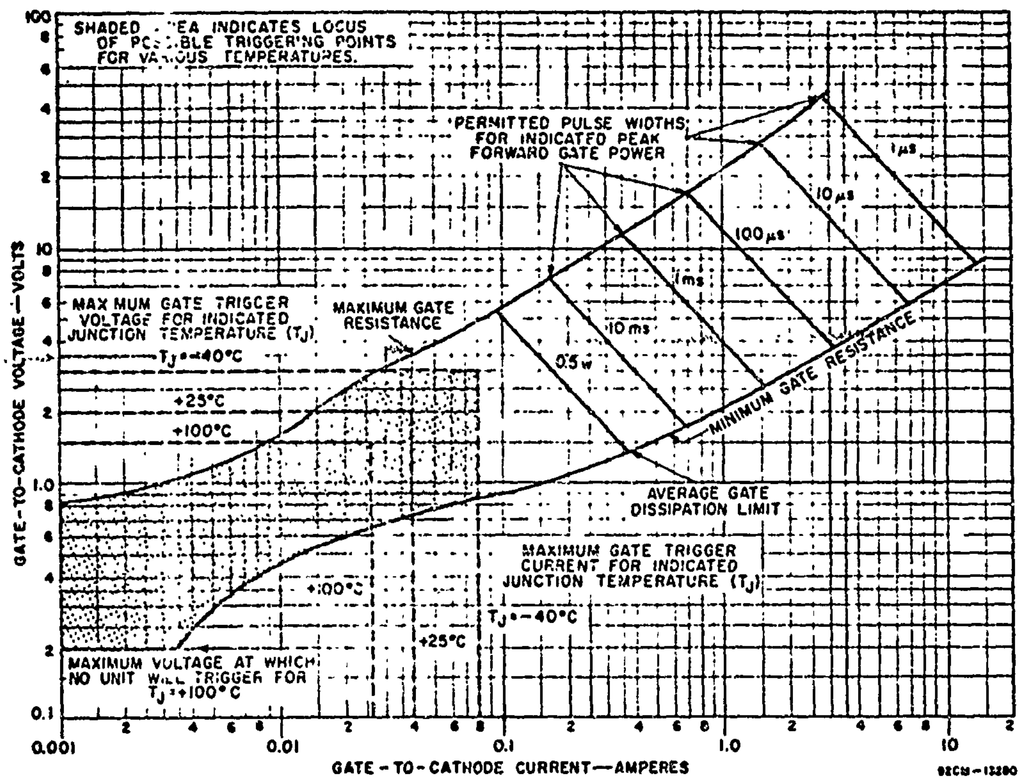


Fig. 23.

TURN-ON TIME CHARACTERISTICS

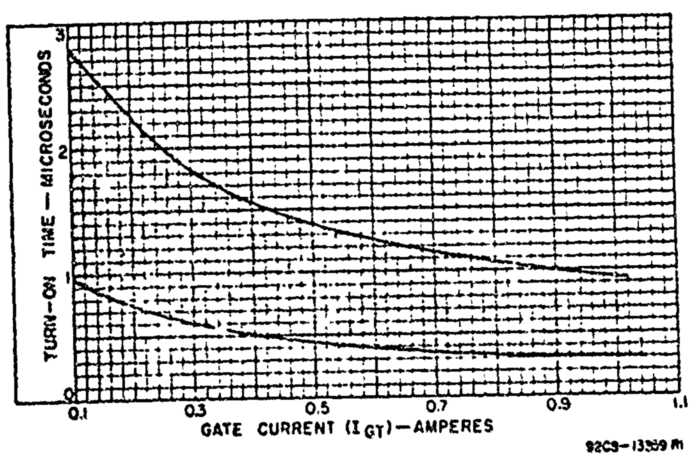


Fig. 24

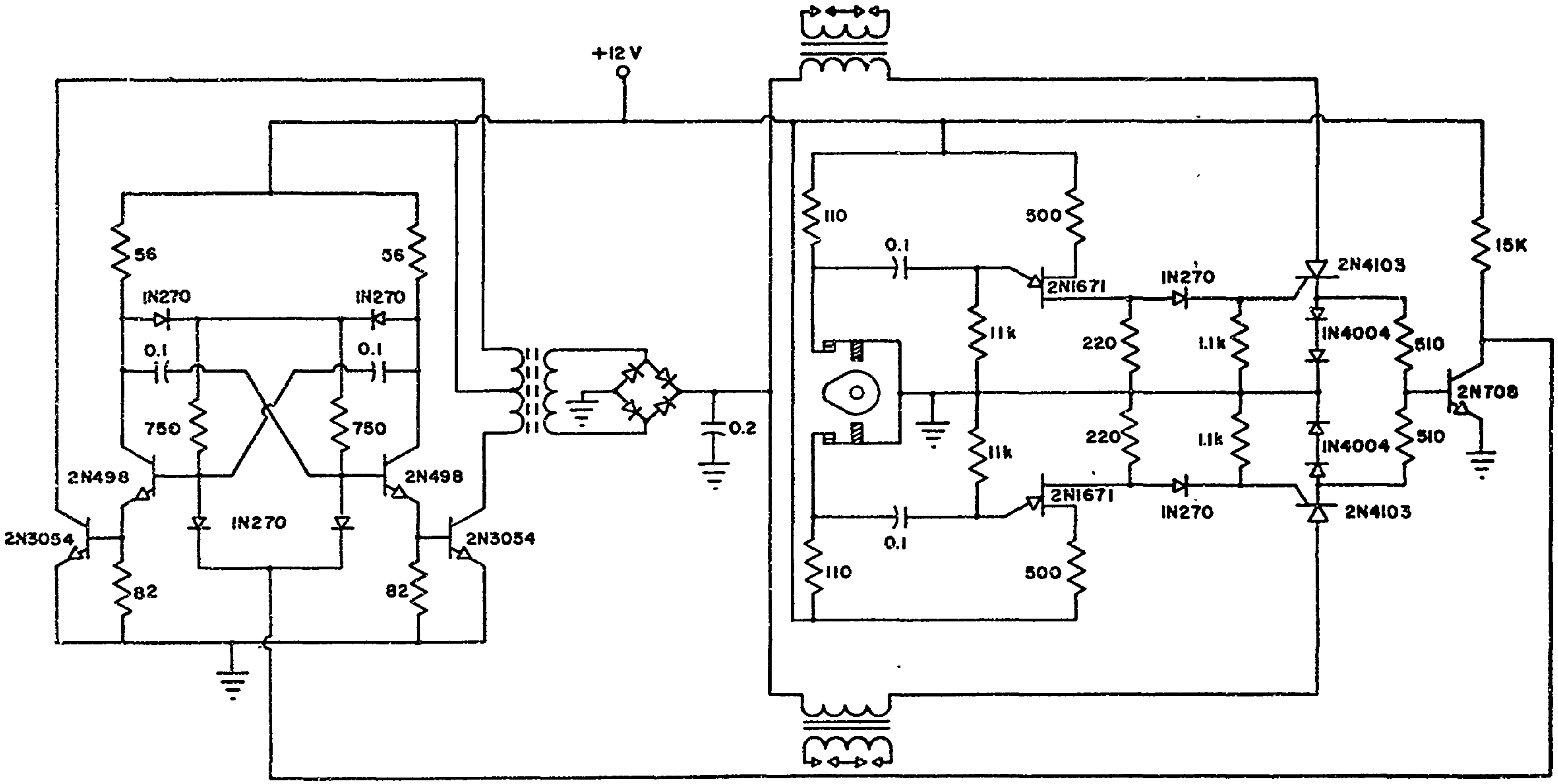


Fig. 25. CDI Schematic Diagram.

VII. CDI SYSTEM TEST AND EVALUATION

The output of the breadboarded CDI system was measured and its characteristics compared to the desired specifications listed earlier and the Hitachi output.

The bench set-up consisted of a small battery identical to the one used for the Hitachi ignition and a breaker plate assembly mounted on a universal motor whose speed was variable from 1,000 to 10,000 rpm. The CDI system was connected to spark plugs mounted on a manifold that was pressurized with nitrogen. Fouling was simulated by placing 500 kΩ non-inductive resistors across each plug.

Nitrogen was chosen as the pressurizing agent since the earth's atmosphere is about four-fifths nitrogen and a source of nitrogen was readily available. The use of nitrogen was not selected to simulate the conditions that exist in the combustion chamber during engine operation but to give a controlled condition on which to compare the Hitachi ignition with the CDI system.

By pressurizing the spark plug manifold with nitrogen worst case conditions were simulated, therefore, cold plugs in a "very lean" mixture.

The following tests were performed on both ignition systems at 1, 4, and 10 thousand rpm:

1. Open circuit
   a. Amplitude
   b. Rise time

2. 500 kΩ load
   a. Amplitude
   b. Rise time

3. Spark plug unpressurized
   a. Amplitude of spike and table
   b. Rise time
   c. Table duration

4. Spark plug pressurized to 15 psi.
   a. Amplitude of spike and table
   b. Rise time
   c. Table duration

5. Spark plug pressurized and 500 kΩ parallel load
   a. Amplitude of spike and table
   b. Rise time
   c. Table duration.

Figure 26 is a record of the Hitachi ignition output measurements as related to the outlined tests. Figures 27 A through E are photographs of the output at an engine speed of 4,000 rpm. On examining the figures it is seen that the ignition system failed to produce an arc for a simulated fouled plug at a high engine rpm. If the manifold pressure was increased to 30 to 45 psi. it produced intermittent firing for test 4 and would not for any test produce an arc at high rpm. These bench tests indicated poor ignition performance under fouled plug conditions.

The same tests were performed with the CDI system. Results are recorded in Fig. 28 and output photographs shown in Fig. 29 A through E.

Key system waveforms are shown in Fig. 30 A through G and depict circuit operation. Figure 31 is a curve of power consumption as related to engine speed. One sees that power input increases with rpm. as desired and is within the value specified in section IV.C.6.

The CDI system was capable of producing an arc when the plugs were pressurized to 125 psi. where the Hitachi system failed at pressures over 40 psi. Thus the CDI system displayed superior performance over the Hitachi system when bench tested under identical conditions.

TEST CONDITION	RPM 1,000	RPM 4,000	RPM 10,000
Input Current (Amps)	2.67	2.3	1.7
Stored Energy (mJ)	53	40	22
TEST I			
Voltage Amplitude (kV)	24	24	16
Rise Time (usec)	44	44	44
TEST II			
Voltage Amplitude	12	10	8
Rise Time	44	44	44
TEST III			
Spike Amplitude (kV)	4.4	4.4	4.4
Table Amplitude (V)	500	500	500
Table Duration (usec)	1300	1300	800
Rise Time (usec)	30	30	30
TEST IV			
Spike Amplitude	7.2	7.2	7.2
Table Amplitude	1000	1000	1000
Table Duration	1000	1000	1000
Rise Time	35	35	35
TEST V			
Spike Amplitude	7.2	7	5
Table Amplitude	500	Inter-	None
Table Duration	800	mittent	
Rise Time	40		

Fig. 26. Hitachi Output.

VERT = 10kV/div

OV-

HOR = 0.5msec/div

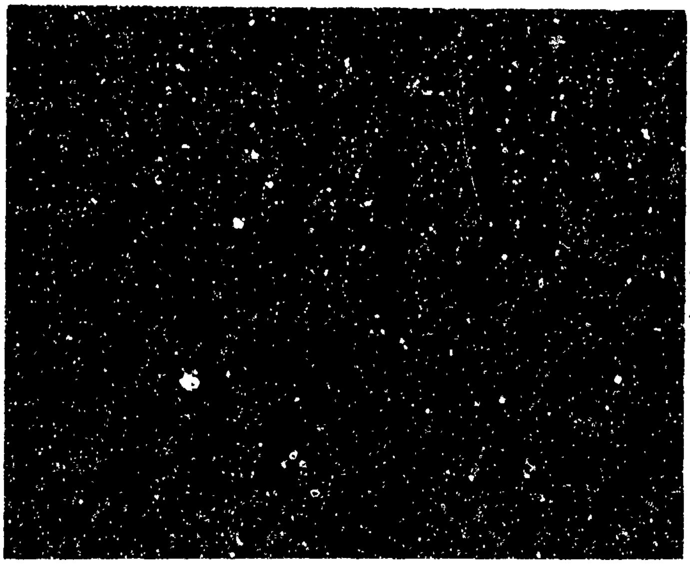


Fig. 27A. Test I. Open circuit voltage, Hitachi System.

VERT = 5kV/div

OV-

HOR = 0.2msec/div

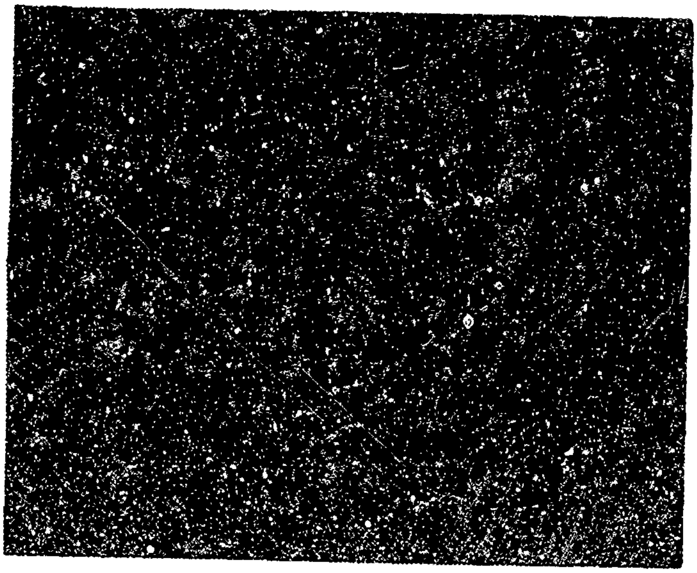


Fig. 27B. Test II. 500 k load, Hitachi System.

VERT = 1kV/div

OV-

HOR = 0.5msec/div

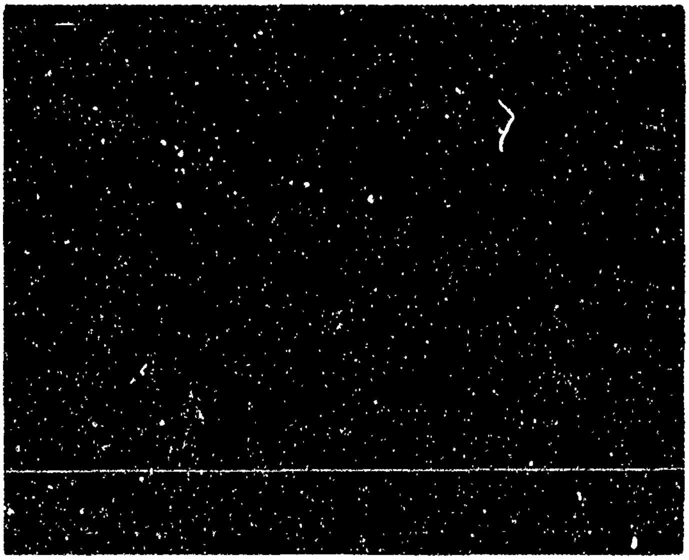


Fig. 27C. Test III. Unpressurized Spark Plug Load.

VERT = 2kV/div

OV-

HOR = 0.5msec/div

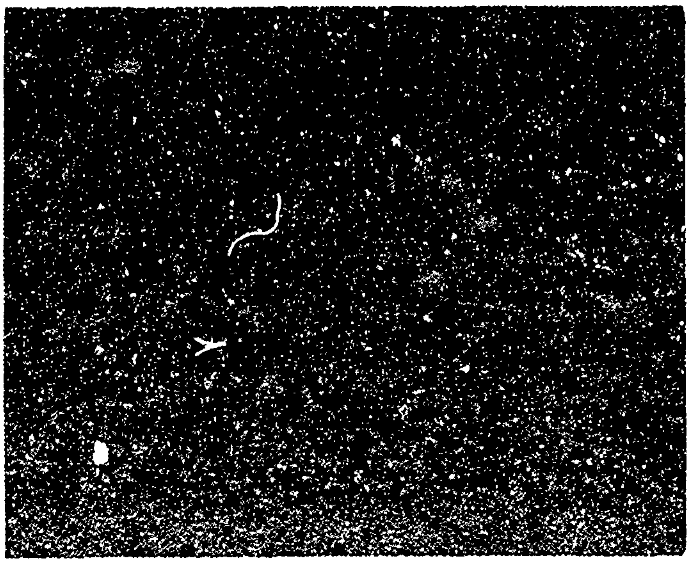


Fig. 27D. Test IV. Pressurized Spark Plug Load, Hitachi System.

VERT = 2kV/div

OV-

HOR = 0.1msec/div

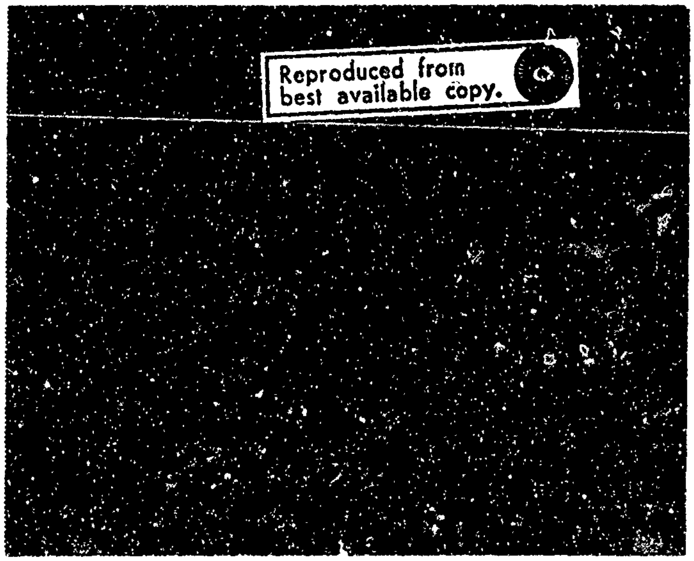


Fig. 27E. Test IV. Simulated Fouled Plug, Hitachi System.

TEST CONDITION	RPM 1,000	4,000	10,000
Input Voltage (V)	560	560	425
Stored Energy (mJ)	31.4	31.4	18
TEST I			
Voltage Amplitude (kV)	28	28	28
Rise Time (usec)	20	20	20
TEST II			
Voltage Amplitude	12	12	10
Rise Time	20	20	19
TEST III			
Spike Amplitude (kV)	5.4	5.4	5.4
Table Amplitude (V)	350	350	350
Table Duration (usec)	250	250	250
Rise Time (usec)	10	10	10
TEST IV			
Spike Amplitude	7	7	7
Table Amplitude	400	400	400
Table Duration	220	220	220
Rise Time	10	10	10
TEST V			
Spike Amplitude	7	7	8
Table Amplitude	500	500	500
Table Duration	220	220	220
Rise Time	12	12	15

Fig. 28. CDI Output.

VERT = 20kV/div

OV

HOR = 0.2msec/div

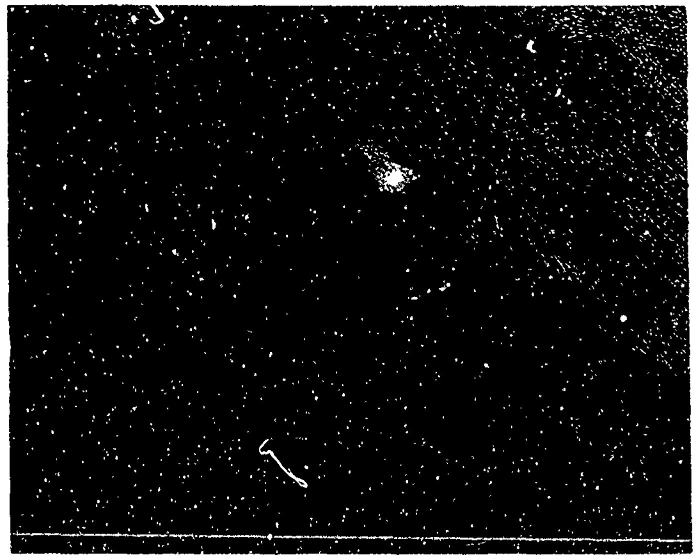


Fig. 29A. Test I. Open Circuit Voltage, CDI System.

VERT = 5kV/div

OV-

HOR = 0.1msec/div

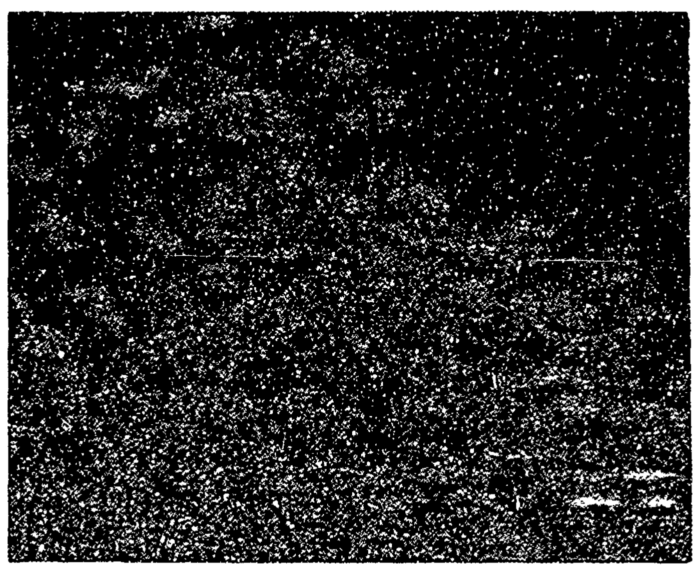


Fig. 29B. Test II. 500 k Load, CDI System.

VERT = 1kV/div

OV-

HOR = 0.2msec/div

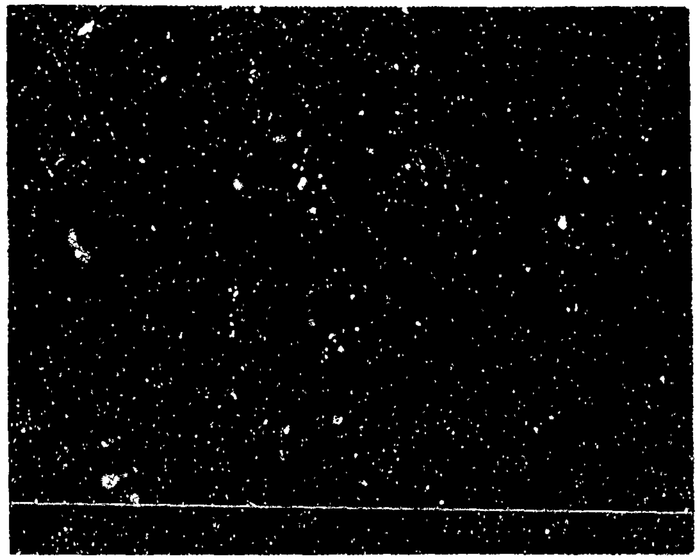


Fig. 29C. Test III. Spark Plug Load, CDI System.

VERT = 1kV/div

OV-

HOR = 0.5msec/div

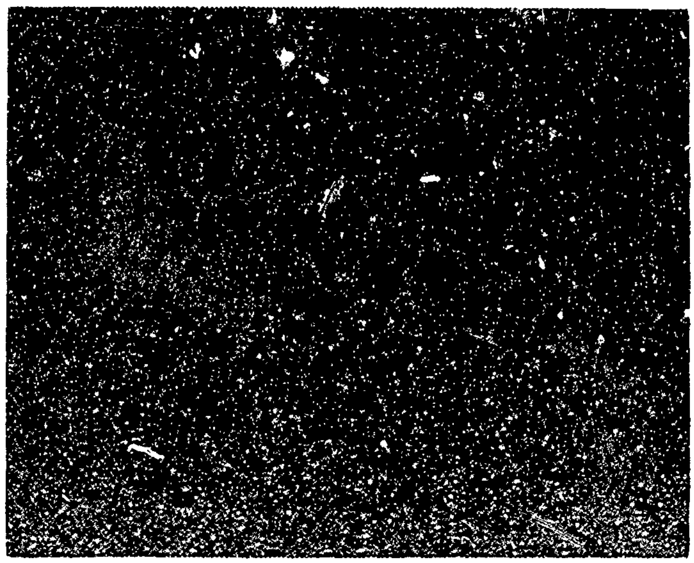


Fig. 29D. Test IV. Pressurized Spark Plug, CDI System.

VERT: 20V/div

Collector: Q1

OV-

VERT: 1V/div
Base: Q1

OV-

HOR: 20usec/div

Fig. 30A. Converter Output Transistor Wave Form.

VERT: 10V/div

Collector: Q3

OV-

OV-

Base: Q3

VERT: 5V/div

HOR: 20usec/div

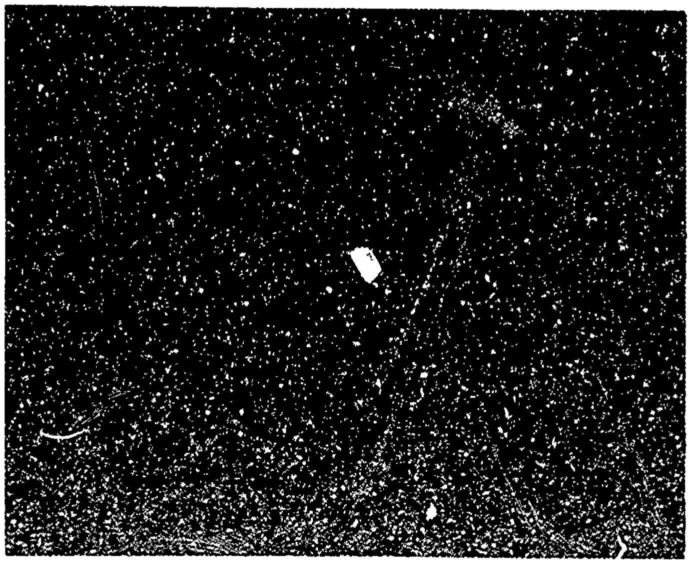


Fig. 30B. Converter Driver Transistor Wave Form.

VERT: 5V/div

SCR Gate

OV-

OV-

Points

VERT: 10V/div

HOR: 2msec/div

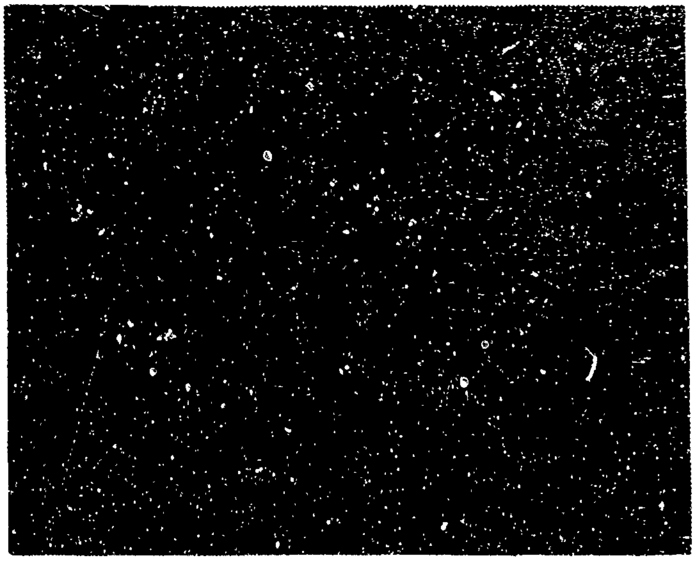


Fig. 30C. Trigger Circuit Wave Form.

VERT: 200V/div

C3 Voltage

OV-

OV-

Voltage Spark Plug

HOR: 2msec/div

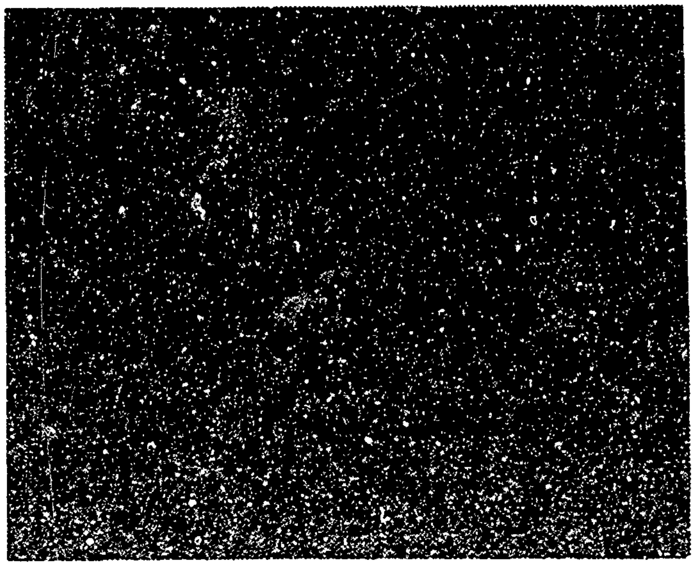


Fig. 30D. Storage Capacitor Charging Wave Form.

VERT: 20V/div

Collector Q1

OV-

CDI Output

OV-

VERT: 1kV/div

HOR: 2msec/div

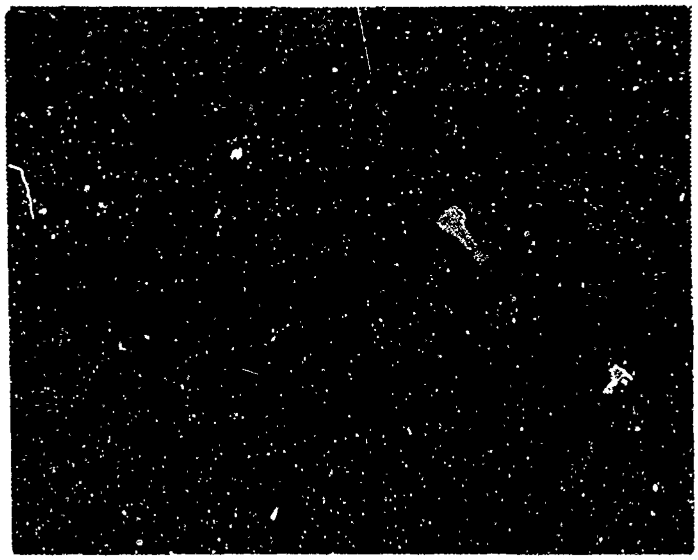


Fig. 30E. Gated Converter Drive to Inverter Transformer Wave Form.

VERT: 2V/div

SCR Cathode

OV-

CDI Output

OV-

VERT: 1kV/div

HOR: 2msec/div

Fig. 30F. MV Gate Input Wave Form.

VERT: 5V/div

Cathode D3 and D4

OV-

CDI Output

OV-

VERT: 1kV/div

HOR: 2msec/div

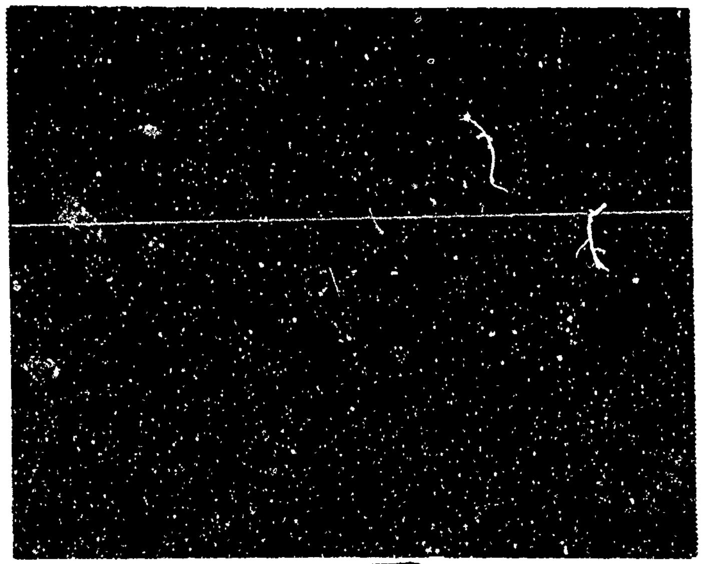


Fig. 30G. MV Gate Output Wave Form.

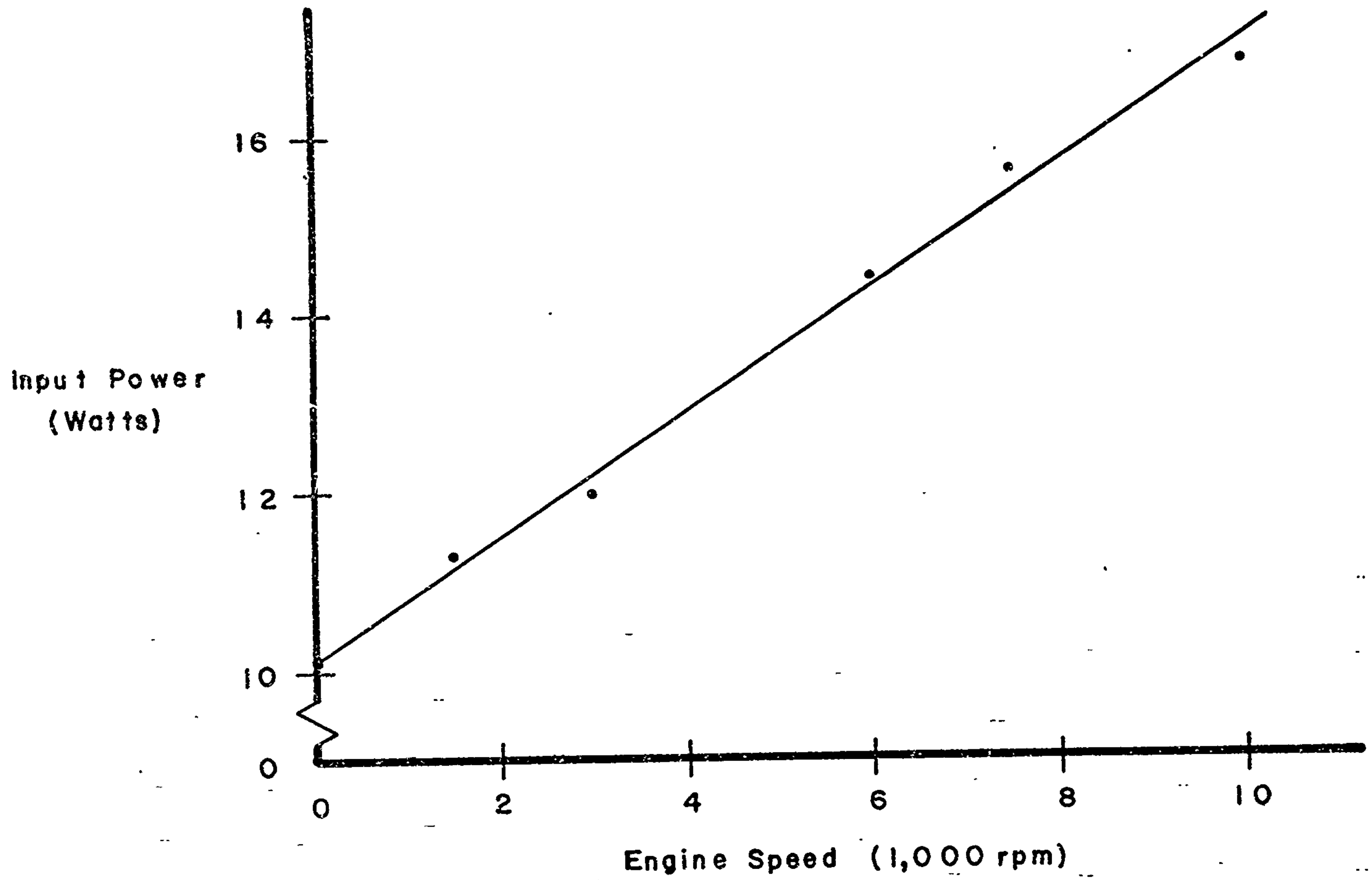


Fig. 31. CDI System Power Consumption

VIII. CONCLUSIONS AND RECOMMENDATIONS

An ignition system is required to replace the aging battery-coil ignition now used on practically every automobile engine in use today. The Kettering system is no longer able to meet modern automotive engine demands, and capacitor discharge ignition systems exhibit superior performance in producing ignition in today's high output engines.

Energy and ionization duration requirements associated with the battery coil system cannot be applied to the CD ignition. New standards need to be derived to best utilize the advantages of the CDI system. Brute force engineering must be eliminated. A CDI system design must meet the conditions imposed by the engine on which it is to be installed in order to prevent an over or under design. Many CDI system design specifications far exceed the requirements necessary to produce ignition.

The initial cost of a CDI system is considerably higher than that of the Kettering. However, maintenance expenses and inconveniences imposed upon the customer must also be considered.

The trend in industry is to cut the production cost of ignition systems, which too often leads to systems having low reliability. To improve reliability, initial system cost should be allowed to rise; reduced maintenance will offset higher prices. The repayment is customer convenience, since CDI systems can be produced having one fourth the maintenance requirements of the old system.

Automotive history clearly refutes the belief that convenience features cannot compete with cost. Certainly, no one can claim that the electric starter replaced the hand crank on a cost basis. The automatic transmission outsells the standard transmission because it is more convenient, not less expensive. High output eight cylinder engines are sold at a price premium in todays market on the basis of performance, obviously not on a lower cost basis. When the added performance and convenience can justify the added cost, the CDI system will be accepted.

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